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ARF Project D113  
Contract No. DA-18-108-CML-5507

ANALYSIS OF SELECTED DISSEMINATION  
AND DESIGN PROBLEMS (U)

Task X

GROUND-TO-GROUND ROCKETS FOR LARGE AREA CW COVERAGE

This document consists of 62 pages  
No. 20 of 40 copies, series

Francois J. Olmer  
Harold D. Black  
Fred B. Smith

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Task X Report

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Task X:

GROUND-TO-GROUND ROCKETS FOR LARGE AREA CW COVERAGE (U)

Prepared by

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**GROUND-TO-GROUND ROCKETS FOR LARGE AREA CW COVERAGE (U)**

**ABSTRACT**

Task X is a study of the coverage of areas by liquid drops ejected from a rocket during its terminal flight. The methods for computing area covered by a rocket or shell using the base ejection system and an ideal spray system are developed. The area contaminated by single rockets is computed. Ground contaminations to be expected are computed for a family of rockets with 16,000 meters maximum range and various diameters, including 4-inch through 8-inch diameter rockets. Ejection mechanisms are discussed.

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ANALYSIS OF SELECTED DISSEMINATION AND DESIGN PROBLEMS (U)

Final Report On Task X

GROUND-TO-GROUND ROCKETS FOR LARGE AREA CW COVERAGE (U)

I. INTRODUCTION

This task was assigned at the Steering Committee Meeting held at Army Chemical Center on 26 September 1956. Task X was defined as follows:\*

"This is a newly assigned task requiring that a study be conducted to determine and propose design criteria for rocket systems to disseminate low volatile liquids as droplets ( $> 3$  mg) for direct attack of personnel as well as for ground contamination.

"This study should be conducted by examining the relationship of variables such as altitude of release of liquid, method of release of liquid (emphasis should be placed on base ejection type), velocity of rocket, physical characteristics of liquid, droplet size, met conditions, ground contamination density, and area coverage. Advantage will be taken of field test data obtained by the British in their work on the 25 pounder base ejection shell.

"It is required that the contractor propose design criteria for this system including size, capacity, altitude of release, burster mechanism, rate of fire, aiming error, etc."

Some of the requirements included in this statement of task impose limitations on the investigation of a rocket weapon which appear to be unnecessarily restrictive. It is difficult to control the ejection of a liquid so large droplets are formed. The production of a particle size distribution which will include very small particles is inherent in the processes of shattering a liquid mass into particles. All the liquid that reaches the target contributes to the effective contamination. A particle size distribution matched to the operating conditions of the munition should be selected to obtain the desired contamination density at ground level. So, the validity of a requirement for droplets larger than three milligrams was questioned soon after the work started. At a Steering Committee Meeting

---

\* Chemical Corps Research and Development Command, Chemical Warfare Laboratories, Army Chemical Center, Maryland, Reference No. CMLRD-CW-R(WR)DA 18-108-CML-5507, 17 October 1956.

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on 12 April 1957, the requirement for droplets larger than three milligrams was removed. It was agreed that the entire particle size distribution reaching the ground would be studied, and while large drops are desired, the size distribution should be fitted to the conditions of the problem within the limits permitted by practical considerations. It was specified that ground contamination densities from  $0.1 \text{ g/m}^2$  to  $1.0 \text{ g/m}^2$  are of interest.

The base ejection system used in the British 25 pounder shell, BE. MK. 8, is simple, but it does not produce a desirable ground contamination pattern. The agent is ejected in a very short period of time and falls on a long narrow area in the direction of the wind. This distribution does not permit efficient juxtaposition of contaminated areas when many rockets are directed at the target. The distribution of agent may be improved by progressively ejecting the agent over a longer period of time during the terminal flight of the rocket. Therefore, it was agreed that any practical method for discharging the agent to disseminate large drops should be considered. The directive to emphasize base ejection systems was removed.

The general problem of distributing agent from free ballistic artillery rockets is investigated. This weapon system is to disperse agent over a large area by ejecting liquid at a height above the ground from each rocket. Neither the rockets nor the mechanisms for ejecting the liquid agent exist. Technical problems connected with the design of new rocket weapons are studied from a theoretical standpoint. Design and development experience is used wherever knowledge gained from previous work is applicable. The results presented are an engineering estimate to be used in further engineering study as a starting place for design work rather than design criteria.

The performance specifications and military characteristics of a weapon are functions of the target to be defeated and the operational conditions in which the weapon may be used. In this study we consider only those physical factors which limit the selection of performance specifications. The study of military situations and the evaluation of military worth of rocket weapons is not part of this task. Military employment of the weapons is considered only to the extent required for the formation of intuitive engineering judgments. The work of this task indicates the performance to be expected from various sizes of fin-stabilized, unguided rockets. This information is

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useful for starting an operational evaluation to determine optimum characteristics for this type of weapon, or for beginning a design study when military requirements are specified.

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**II. GENERAL DISCUSSION**

The rocket weapons are to achieve rapid contamination of large areas. They are to fill a gap in the array of chemical weapons by providing the great firepower necessary to defeat large area targets of opportunity. They are not expected to have the precision of artillery, nor are they to replace mortars and other organic weapons suitable for smaller targets at shorter ranges. The light weight and high rates of fire possible with rocket launchers make the attack of large areas by small mobile units feasible.

The shape and size of the area to be contaminated is one of the most important factors influencing the selection of an area coverage weapons system. The area coverage weapons would probably be assigned at the divisional level, and used in the support of combat groups. This and other factors involved in Task X led to the selection of the area that one battalion may occupy as suitable for the study. Operations research studies and combat problems indicate that a battalion size organization may be dispersed over an area of three million square meters. The exact size and shape of this area is governed by mission, terrain, progress of battle, command decisions, communications facilities, weather, and chance. It is impossible to select one simple target model that adequately describes the variety of expected field situations. However, the study of methods for contaminating an area of  $3 \times 10^6 \text{ m}^2$  yields information that may be extrapolated or interpolated to fit other situations.

It is expected that the disposition of troops within a target area will be unique for each situation, and there will be great variations in density of men and materiel within the target. For this work it is assumed that a uniform density of contamination over the area is desired. It is assumed that equal fractions of the target area are of equal importance. A consideration of accuracy of intelligence, speed of communications, delays between command and execution, mobility of the enemy and possible variations in deployment of the enemy tends to justify these assumptions. Degrees of protection and evasive actions possible to the enemy are not considered. Contamination density is the only criteria for terminal effects on the target.

A typical target may be troops deployed along a road or river bank. The meandering of the terrain feature would depend on the terrain itself.

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This would normally be far from a straight line. However, personnel of the Operations Research Office suggested an elongated rectangular area 300 meters wide and 10,000 meters long as a convenient representation of a typical target expected to occur frequently in future combat. Fitting this general configuration to maps of western Europe indicated that the rocket weapons should have a reasonably long range as well as tactical mobility to provide flexibility in use.

Maximum range strongly influences both the cost and value of the weapons system. This is an important parameter of weapons evaluation studies. Maximum range not only dictates what targets may be engaged, but also strongly influences the number of units required to accomplish a specific mission. This study did not attempt to balance cost, weight, mobility, men, etc. against maximum range. A very cursory examination indicated that a rocket weapon having maximum range of 16,000 meters would have adequate flexibility to engage battalion size targets.

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**III. ROCKET DESIGN**

The design of the rocket is intimately related to the method of ejecting the agent at the target and the resulting ground contamination achieved. The angle of fall and velocity of the rocket during the period of ejection of the agent are important to the determination of the ejection system, fuze functioning, particle size distribution, and ground contamination pattern. The agent and ejection mechanism are the payload that the rocket must carry. Thus a feedback of information was required between the activities of this task. Rocket design computation were conducted throughout the duration of the task.

Fin-stabilized rockets without boost were selected for this study. These are to be launched from simple rail-type launchers. The launching rails are twice the length of the rockets. Steel having 100,000 psi yield strength were selected for head and motor components (except ejection piston). Aluminum having 70,000 psi yield strength was selected for the fin and fairing assembly. The interior motor wall and bulkhead are ceramic-coated to a thickness of 0.03 inches. The nozzle is steel with a ceramic insert. Six fixed fins having an envelope diameter twice the motor diameter are used in all rocket computations.

The equations of motion were solved step by step over equal increments of time to yield trajectory information. The first computations were based on a minimum drag shape. The low drag shape resulted in high velocities of approach to the ground, which complicated the ejection problems. Furthermore, this head shape was not convenient for an ejection mechanism. Therefore a shape similar to the 2.75-inch FFAR was chosen, and drag data for the FFAR were used in the rocket computations.

Table 1 is comparison of 4-1/2-inch rockets. The agent weight is held constant while all other quantities reflect the change in range from 16,000 meters to 12,000 meters. Table 2 compares a family of rockets designed for 16,000 meter maximum range.

Variable time fuzes were selected for initiating the ejection mechanisms. The setting of time fuzes introduces complexity to the system and additional sources of error. The time of flight to short ranges is dependent upon ambient temperature. While fuzes may be compensated for, temperature or the settings may be corrected for temperature. This introduces fuzing complexities greater than those resulting from the use of variable time fuzes.

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Table 1

**COMPARISON OF 4-1/2-INCH ROCKETS**

Maximum Range, ft	52,500	39,400
Agent Weight, lbs	6.8	6.8
Total Weight, lbs	85.0	64.0
Length, in.	90.0	72.0
Burnt Weight, lbs	51.0	43.6
Propellant Weight, lbs	34.0	21.0
Burning Time, sec	5.0	2.5
Thrust, lbs	1,360	1760.0
Nozzle Weight, lbs	3.3	3.0
Fins and Fairing, lbs	2.8	3.1
Fuze, lbs	2.5	2.5
Ejection System, lbs	2.8	2.6

Table 2

**FAMILY OF ROCKETS**

Diameter, in.	4	4-1/2	5	6	7	8
Total Weight, lbs	68	85	112	172	247	345
Agent Weight, lbs	3.52	6.8	11.0	25.7	54.3	103.4
Length, in.	87	90	96	101	109	117
Burnt Weight, lbs	38.2	51.	70.8	116.7	175.2	255
Propellant Weight, lbs	29.8	34.0	41.2	55.3	71.8	90.0
Thrust, lbs	1192	1360	1648	2212	2872	3600

Maximum Range = 52,500 ft

Burning Time = 5 sec

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**IV. ROCKET LAUNCHERS**

The ratio of agent to total weight of rocket is more attractive for the heavier rockets than the small ones. Comparison of area coverage per rocket makes the larger sizes even more attractive. Therefore, primary consideration was given to a launcher for the 8-inch rockets. A launcher loaded with seven 8-inch rockets may be carried on, and fired from a standard 2-1/2-ton truck. Power for elevating and traversing the launcher may be taken from the truck engine.

The completely loaded 8-inch rocket launcher would weight less than 5,000 pounds. Hand elevating and traversing mechanism could be supplied for emergency use. The total crew could consist of the driver and two men. The total time for preparation to fire should take less than ten minutes. The rockets could be fired alternately at one-second intervals, or time could be taken to reset to a different aiming point for each rocket. If this system were used, 11 rocket-launching vehicles could contaminate the area occupied by one or more enemy battalions.

Preliminary computations indicate that 25 of the 4-1/2-inch rockets could be fired from a launcher mounted on a standard 2-1/2-ton truck. This offers the advantage that the rockets could be loaded onto the launchers by manpower. However 40 trucks would be required to accomplish the mission of 11 trucks loaded with 8-inch rockets.

**V. GROUND COVERAGE BY A SINGLE ROCKET****A. General Consideration**

In the British 25 pounder, the agent is ejected almost instantaneously by a propellant charge. The agent then falls on the ground to cover a long and narrow area in the direction of the wind.<sup>1</sup> The shape of this area cannot be controlled either to fit the target or to insure efficient juxtaposition when many rockets are directed at the target. Furthermore, the ground density within the contaminated area is highly variable. Some points on the ground receive considerably more agent than required, extensive areas receive too little.

The ground distribution can be considerably improved, with respect both to its uniformity and to the shape of its boundaries, by ejecting the agent for a finite time during the terminal flight of the rocket. The next section defines the characteristics of such an ideal system.

**B. Area Contaminated by a Single Rocket**

Consider a rocket falling to the ground along path AB (Fig. 1) making an angle  $\theta$  with the horizontal plane. Let the wind direction coincide with X-axis and let  $\phi$  be the angle between the wind direction and the plane of the trajectory.

The agent is first ejected at A, altitude H. The largest drops hit the ground at M; the smallest, at N. The ejection ceases at B. Again, the largest drops hit at P; the smallest, at Q.

Since altitude H is small, the atmosphere between H and the ground may be considered as homogeneous. Since the size of the droplets is small, we shall assume that the drops reach their terminal velocity immediately after being released.

The terminal velocity,  $v$  of small diameter ( $d < 500\mu$ ) droplets in, say, ICAN atmospheres is accurately represented<sup>2</sup> by:

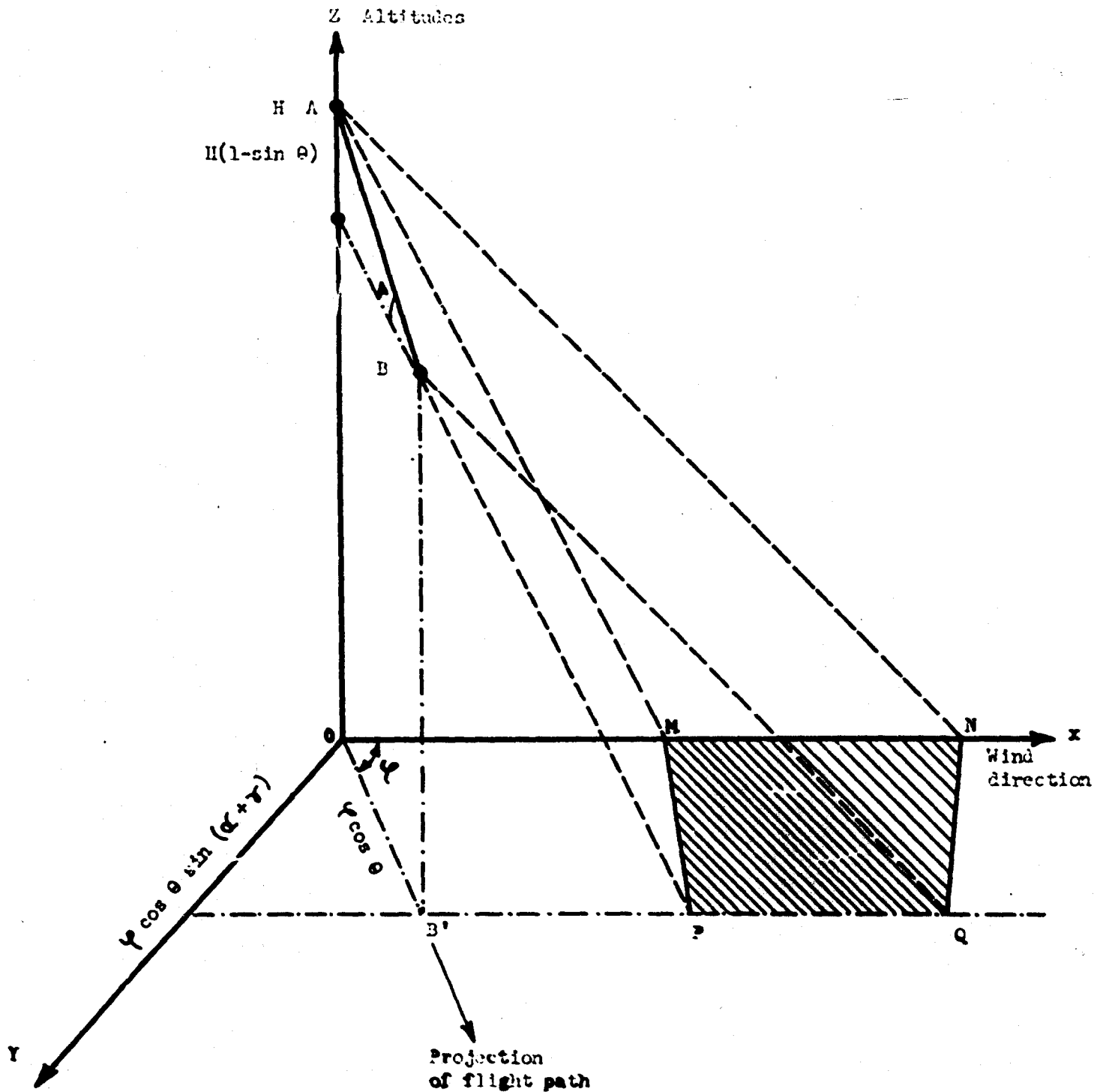
$$v = 3780 d$$

---

<sup>1</sup>Porton Technical Paper No. 548.

<sup>2</sup>Best, A.C. Quarterly J. Meteorological Society, p. 76, 302, 1950.

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**Fig. 1** **GROUND CONTAMINATION**

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and the drift from ground zero, by:

$$x = \frac{WH}{3780 d}$$

where H = altitude of ejection

W = wind velocity

d = drop diameter.

The contaminated area MNPQ is trapezoidal in shape since the distance MN decreases with H.<sup>1</sup>

The height of trapezoid MNPQ in Fig. 1 is

$$w = AB \cos \theta \sin \varphi \quad (3)$$

If Q is the quantity of agent contained in the rocket; R, the rate (assumed to be constant for the moment) at which the agent is ejected and v, the velocity of the rockets:

$$AB = \frac{vQ}{R} \quad (4)$$

Thus:

$$w = \frac{vQ}{R} \cos \theta \sin \varphi \quad (5)$$

This equation gives the width (crosswind) of the contaminated area.

All the drops ejected from the rocket fall inside the trapezoidal area MNPQ Fig. 1 on the ground. However, the degree of contamination within this area is far from being uniform and the boundaries of the area subjected to a given dosage is irregular.

The contamination density in a downwind direction, say along MN, depends on the mass distribution of the drops ejected from the rocket. If, for instance, the mass distribution is uniform, as shown diagrammatically in Fig. 2a, the density  $\Delta$  decreases sharply with increasing distances from ground zero

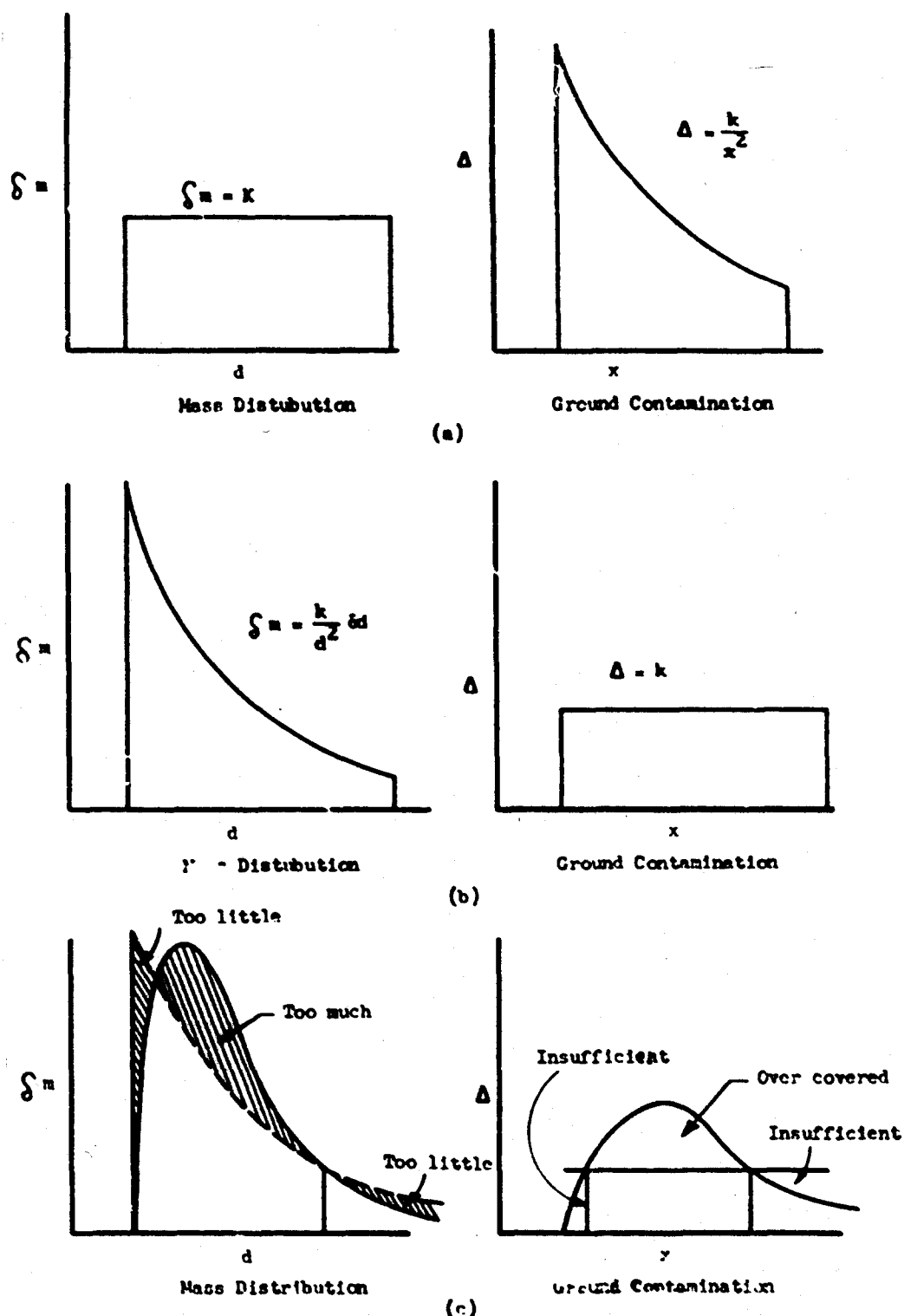
$$\Delta = \frac{\delta m}{\delta x} = \frac{\delta m}{\delta d} \frac{\delta d}{\delta x} = \frac{k}{x^2} \quad (6)$$

To obtain a uniform ground density, the mass distribution would have to obey

$$\delta m = \frac{k}{d^2} \delta d \quad (7)$$

---

<sup>1</sup> Effects due to diffusion are neglected for the moment.



**Fig. 2 GRAPHICAL RELATIONSHIP BETWEEN MASS DISTRIBUTION AND GROUND COVERAGE**

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as indicated in Fig. 2b. In other words, it would have to contain many drops of small diameter, few of large ones.

The actual mass distribution produced by the ejection system is not known accurately. Data from a Porton paper<sup>1</sup> indicates that the distribution may be fitted by a normal logarithmic distribution:

$$\frac{\delta m}{m} = \frac{2}{\sqrt{2\pi}\sigma} \exp - \frac{(\log d/d_0)^2}{2\sigma^2} \partial(\log d/d_0) \quad (8)$$

where  $\sigma = 0.40$  and  $d_0$  is the diameter corresponding to the peak of the distribution ( $d_0 = 140\mu$ ). Taking Eq. 2 into consideration, this expression may be rewritten:

$$\frac{\delta m}{m} = - \frac{1}{\sqrt{2\pi}\sigma} \exp - \frac{(\log x/x_0)^2}{2\sigma^2} \partial(\log x/x_0) \quad (9)$$

The density  $\Delta$  in the wind direction is therefore

$$\Delta = \frac{\delta m}{\delta x} = - \frac{m}{\sqrt{2\pi}\sigma x} \exp - \frac{(\log x/x_0)^2}{2\sigma^2} \quad (10)$$

with

$$x_0 = \frac{WH}{3780 d_0}$$

Plots of  $\Delta$  for various  $X_0$ , that is, as a function of  $H$  are found to be almost identical with the experimental ground coverages presented in Fig. 14 of the Porton paper. A typical ground coverage from Eq. 10 is reproduced in Fig. 2c. The curve has a peak at low values of  $X$ , indicating that the mass distribution, Eq. 8, contains too little of the small and large droplets and too much of the medium ones. Such a distribution is clearly inefficient since some areas on the ground receive too high a dosage while others receive too little. These deviations from the theoretical mass distribution of Fig. 2b are indicated by the cross hatched areas on Fig. 2c. In the typical distribution reported in the Porton paper, as much as 75 per cent of the agent is wasted by improper distribution of the drop diameters.

In the following, we shall consider, in turn, the ground contamination produced by two systems of progressive ejection:

- a. a system giving a logarithmic mass distribution of drops, as in the British 25 pounder.
- b. a system giving the ideal mass distribution:

---

<sup>1</sup>Porton Technical paper No. 548, Fig. 3. p. 19.

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$$\delta m = \frac{k}{d^2} \delta d$$

The first system is an adaptation of the British base ejection system. Possible means of realizing this adaptation are presented in discussion of practical systems. The second system is purely speculative. The possibility of realizing it is remote. However, an intermediate system, better than the British one, may probably be developed after experimental information becomes available. Comparison of the performance of the two systems discussed here will indicate the lower and upper limits to be expected in the ground-to-ground coverage by rockets.

## C. Contamination from a Logarithmic Mass Distribution System

### 1. Ground Coverage

The ground coverage obtained when the agent is progressively ejected from the falling rocket may be visualized by a three-dimensional surface such as that sketched in Fig. 3. This surface is given by Eq. 10 when both  $X$  and  $H$  (through  $X_0$  in expression 2) are varied. The area within which the density is equal to or exceeds a predetermined value  $\Delta_0$  is represented by the boundary ABCDE, i. e., the intersection of the three-dimensional surface by a plane of coordinate  $\Delta_0$ . Area ABCDE is bounded in the direction parallel to the wind by the two straight lines AB and ED.<sup>1</sup> To the lee and windward, it is bounded by two curves, AE and BCD, whose expressions will be derived later.

When the ejection of the agent is instantaneous, surface ABCDE reduces to a thin, cigar-shaped pattern whose width is controlled by the diffusion. This limiting area is the isopleth from a point source ejected at altitude  $H$ .<sup>2</sup>

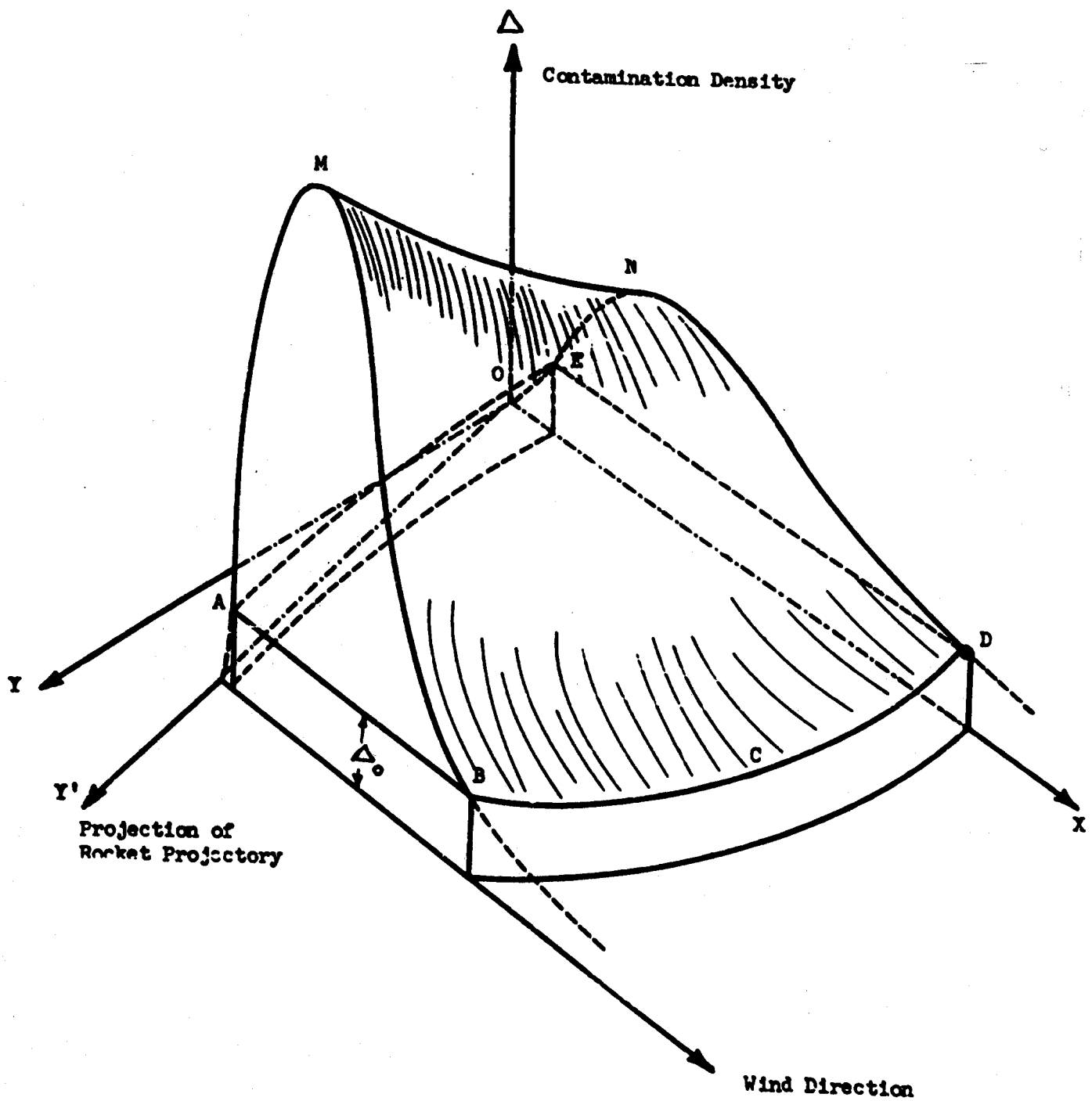
Figure 3 shows that the distribution of the agent on the ground has several undesirable features. First the distribution is uneven in the wind direction, as illustrated by the peak of a vertical section such as END. This is due to the distribution of drop size from the ejection system. Second,

<sup>1</sup>Again neglecting diffusion. Diffusion causes these lines to bulge very slightly outward (see Fig. 12 of the Porton paper).

<sup>2</sup>These isopleths have been calculated and appear in ARF Report D086, RDO No. 555-871-SR 12, Design Parameters for Special Warhead for Guided Missiles, SECRET.



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**Fig. 3 GROUND COVERAGE FROM BASE EJECTION SHELL**

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the distribution is uneven in the crosswind direction as illustrated by the slope of a line such as MN. This is due to the decrease in altitude of the rocket during ejection. Third, the boundaries of the area receiving the concentration  $\Delta_0$  are irregular, requiring that the individual areas be overlapped in order to cover an extensive target area. An ideal ground dispersion should be represented by a horizontal surface with vertical sides.

Let us now determine the length in the wind direction of the pattern of contamination corresponding to the ejection of a logarithmic distribution. Expression 10 given earlier represents the linear coverage in the wind direction. Along a thin strip of width  $\delta w$ , the area coverage is

$$\Delta = \frac{m}{\partial X \delta w}$$

The width  $\delta w$  corresponds to the elemental time  $\delta t$  of the rocket flight.

$$\delta w = v \delta t \cos \theta \sin \varphi \quad (11)$$

where  $v$  is the terminal velocity of the rocket. This appears clearly on Fig 1. Also

$$\partial m = R \partial t$$

where  $R$  is the rate at which the agent is ejected.

Therefore

$$\Delta = \frac{R}{\sqrt{2\pi} v \cos \theta \sin \varphi} \frac{1}{X} \exp - \frac{(\log x/x_0)^2}{2\sigma^2} \quad (12)$$

The variations of  $\Delta$  with altitude  $H$  are obtained by replacing  $X_0$  in Eq. 12 by

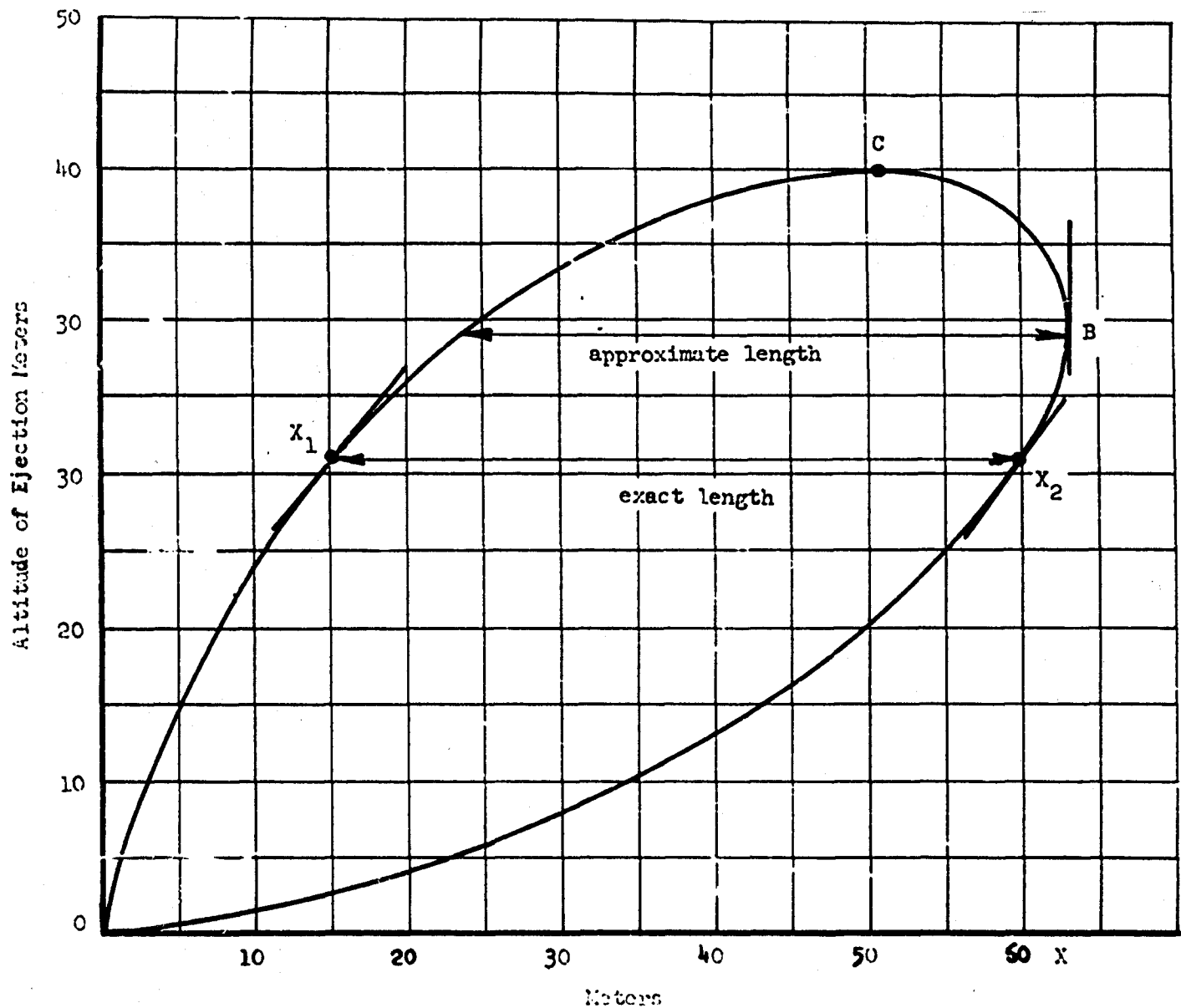
$$X_0 = \frac{WH}{3780 d_0} \quad (13)$$

The downwind boundaries of the area subjected to density  $\Delta_0$  are obtained by solving Eq. 12 for  $H$

$$H = \frac{3780 d_0 X}{W} \exp \mp \sqrt{2\sigma^2} \log \frac{R}{\sqrt{2\pi} v \cos \theta \sin \varphi \Delta_0 X} \quad (14)$$

This gives the expression of the two curves AE and BCD on Fig. 3 referred to axis OY. A plot of Eq. 14 for arbitrary values of the parameters appears in Fig. 4. As expected, when  $H=0$ , the two boundaries  $X_1$  and  $X_2$  are zero. This corresponds to the case where the agent is ejected near the ground, that is, where all the agent is concentrated over a small distance. As  $H$  increases,

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**Fig. 4** VARIATION OF LENGTH CONTAMINATED TO A GIVEN DENSITY  
WITH HEIGHT OF EJECTION

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the boundaries diverge and the length of the contaminated area increases. When  $X$  reaches a value such that the logarithm in Eq. 14 becomes zero, the two boundaries again merge. This corresponds to point B on the figure.

The highest altitude of release, (point C) giving a ground density  $\Delta_0$  is given by

$$\frac{\partial H}{\partial X_2} = 0$$

$$H_{\max} = \frac{3780 \Delta_0}{W} \frac{R}{\sqrt{2\pi} v \cos \theta \sin \phi \Delta_0} e^{\frac{\sigma^2}{2}} \frac{1}{\sigma} \quad (15)$$

This corresponds to the case where the altitude of ejection is so high that the agent is now spread over a large distance and the contamination nowhere reaches the desired value.

It appears immediately that the agent is most effectively used when it is ejected around a mean altitude,  $H_0$ , for which the length,  $L$ , of the contamination pattern on the ground:

$$L = X_2 - X_1$$

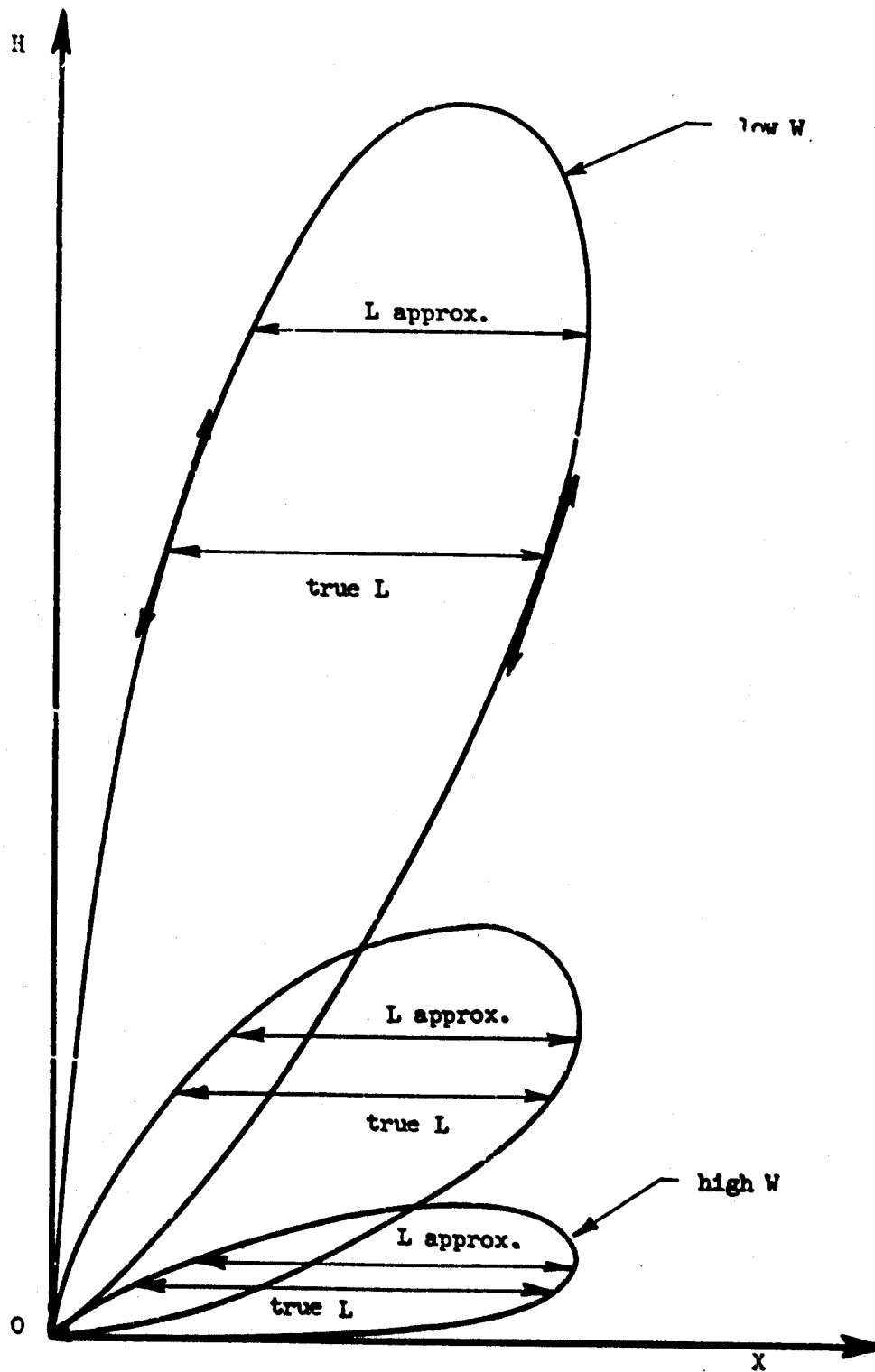
is greatest. This is the point where the slopes of the two boundaries in Fig. 4 have the same value

$$\frac{\partial H}{\partial X_1} = \frac{\partial H}{\partial X_2} \quad (16)$$

However, this equality leads to a transcendental function which cannot be solved formally. While the most efficient altitude might be computed for each combination of parameters, it is desirable to have an analytical expression of  $H_0$ , even approximate, in order to investigate further the relationship between all design parameters.

An approximate expression of  $H_0$  can be obtained by taking the ordinate for which the slope of the far boundary in Fig. 4, that is, the slope of the curve at point B is infinite. The validity of this approximation appears immediately by observing Fig. 5. This figure reproduces, as does Fig. 4, the variations of Eq. 14, that is, the boundaries of the contaminated zone as a function of altitude for three different values of the wind velocity,  $W$ .

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**Fig. 5 VARIATION OF OPTIMUM HEIGHT OF EJECTION  
WITH WIND SPEED**

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It appears immediately that the approximation on  $H_0$  is good when  $W$  is large; poor, when  $W$  is low. However, in the latter case, the graph shows that even large variations in the altitude of release do not seriously affect the length of the contaminated area. Since our chief interest here is to obtain the length of contamination, we feel justified in using the proposed approximation of  $H_0$ .

The value of  $H$  is

$$H_0 = \frac{3780 d_0}{W} \frac{R}{\sqrt{2\pi} \sigma - v \cos \theta \sin \phi \Delta_0} \quad (18)$$

indicating that the optimum height of release decreases as the wind velocity,  $W$ , increases. This result is in agreement with the Porton observation (Porton Paper 538, p. 3) and the graphical results of Fig. 5.

The length,  $L$ , of the contaminated area when the agent is released around the mean altitude  $H_0$

$$L = X_2 - X_1$$

is obtained by combining Eqs. 18 and 14 to obtain

$$L_0 = \frac{W H_0}{3780} \frac{1 - e^{-2\sigma^2}}{d_0} \quad (19)$$

## 2. Individual Area Coverage

By combining Eq. 5 giving the width (crosswind) of the contaminated pattern, Eq. 19 giving its optimum length (downwind) as well as Eq. 18 we now express the area covered by a single rocket

$$a = wL = \frac{Q}{\Delta_0} \left( \frac{1 - e^{-2\sigma^2}}{\sqrt{2\pi} \sigma} \right) \quad (20)$$

The area depends only on  $Q$ , the quantity of agent carried by the rocket and is inversely proportional to  $\Delta_0$ , the desired dosage on the ground.

Area  $A$  varies in some complicated fashion with  $\sigma$ , the standard deviation of the logarithmic mass distribution of the drops ejected from the rocket. This is not unexpected: if all the agent were ejected in drops of the same diameter, the contaminated area would be small since all the drops would fall on the same point on the ground. Conversely, if the drop size

covered a very wide range, the agent would drift over a large area, the over-all contamination would be low and the area subjected to density  $\Delta_0$  again would be small.

The optimum value of  $\sigma$  is obtained by equating

$$\frac{d}{d\sigma} \left( \frac{1 - e^{-2\sigma^2}}{\sigma} \right) = 0 \quad (21)$$

which gives approximately:

$$\sigma = 0.80$$

This value is twice as large as that observed experimentally in the case of the British 25 pounder. In other words, the efficacy of the British weapon or of a progressive logarithmic ejection system may be increased by about 20 per cent by increasing the spread of the drop sizes.

The following table compares the areas of the individual contamination patterns given by instantaneous ejection, as reported in the Porton Paper, and calculated from Eq. 20, for two values of  $\sigma$ .

Table 3  
**AREAS COVERED BY THE INSTANTANEOUS  
AND PROGRESSIVE EJECTION OF 585 GRAMS OF AGENT**

Density g / m <sup>2</sup>	Area Covered (m <sup>2</sup> )		
	Porton Data	Equation 20	
	(instantaneous ejection)	(progressive ejection) $\sigma = 0.40$	$\sigma = 0.80$
0.1	1463	1580	1900
0.5	170 (extrap)	790	950
1.0	Negligible	158	190

The advantage of the progressive ejection system is particularly significant at the highest values of the density.

We shall see later that, by using the inverse square law distribution, the results of the last column are multiplied by a factor of 3.

## D. Coverage When the Drop Sizes Are Distributed According to the Inverse Square Law

In this simple case, the density of the agent on the ground is uniform. From considerations similar to those in the case of the logarithmic distribution, the downwind length of the contaminated area is found to be

$$L = \frac{WH}{3780} \left( \frac{1}{d_s} - \frac{1}{d_e} \right) \quad (22)$$

where  $d_s$  and  $d_e$  are the limiting values of the drop diameters at the small and large end of the distribution.

In order to obtain the density  $\Delta_o$  on the ground, the height,  $H_o$ , and rate,  $R_o$ , of ejection must satisfy

$$\frac{R_o}{H_o} = \frac{W \Delta_o v \cos \theta \sin \phi}{3780} \left( \frac{1}{d_s} - \frac{1}{d_e} \right) \quad (22)$$

By increasing the rate and height of ejection by the same ratio, the length of the pattern is extended in the wind direction and its width, crosswind, correspondingly reduced.

As the rocket falls to the ground, its altitude  $H_c$  decreases as

$$H_t = H_o - vt \sin \theta$$

and the rate of ejection must therefore be reduced as

$$R_t = R_o \left( 1 - \frac{vt \sin \theta}{H_o} \right) \quad (23)$$

in order to maintain  $\Delta_o$  at its initial value.

The ground coverage is, of course

$$a = \frac{Q}{\Delta_o}$$

when the rate of ejection is decreased according to Eq. 23. Comparison with Eq. 20 shows that this area is more than 3 times larger than the area obtained when the agent is ejected to produce a logarithmic mass distribution of drops.

## E. Variations in the Shape of the Pattern of Contamination

Referring once more to Eq. 23 giving the area contaminated by a single rocket, using a progressive ejection, we observe that the shape of the pattern, that is the ratio;

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$$\frac{\text{length downwind}}{\text{width crosswind}}$$

can be modified by altering the rate of ejection,  $R$ . For instance, the length of the pattern increases with a rise in  $R$  (see Eq. 19). Raising  $R$  decreases the duration of ejection of a mass  $Q$  of agent. This, in turn, causes the width of the pattern to be reduced, the area remaining constant. When  $R$  is altered, the optimum altitude of ejection must also be modified as indicated by Eq. 18. In other words, the pattern may be made to extend in the wind direction by increasing  $R$  and  $H_0$  in the same ratio. The pattern may be made to extend in a crosswind direction by lowering  $R$  and  $H_0$ .

This conclusion is readily visualized by inspection of Fig. 6. This figure shows the boundaries on the ground of two contaminated areas obtained from a rocket aimed at point 0. The two curves were obtained by plotting the values of  $X$  from Eq. 13 in abscissa and the instantaneous crosswind position of the rocket,

$$Y = vt \cos \theta \sin \phi$$

as it falls to the ground, in ordinate.

In curve 2, the rate of ejection is three times that in curve 1; the optimum altitude of release is three times that in curve 1. Since  $R$  is three times as large, the time during which the agent is released, and, consequently, the width of the contaminated area shown by crosshatching is correspondingly reduced. Thus, we may obtain at will a long and narrow pattern as in curve 2, or a broad and short pattern, as in curve 1, a flexibility which is not available in the instantaneous release system.

## F. Conclusions

It will be seen in Part VI that the coverage of large areas by a given number of rockets is determined chiefly by the size of the contamination pattern of the rocket. Modification of the other parameters at our disposal affects only slightly the coverage.

Therefore, the greatest opportunity to increase the efficiency of the system consists in developing an ejection mechanism whose performance is as close as possible that of the ideal system described in section D. In other words, the most fruitful line of approach would include either of the following steps, listed in the order of their potential gains:

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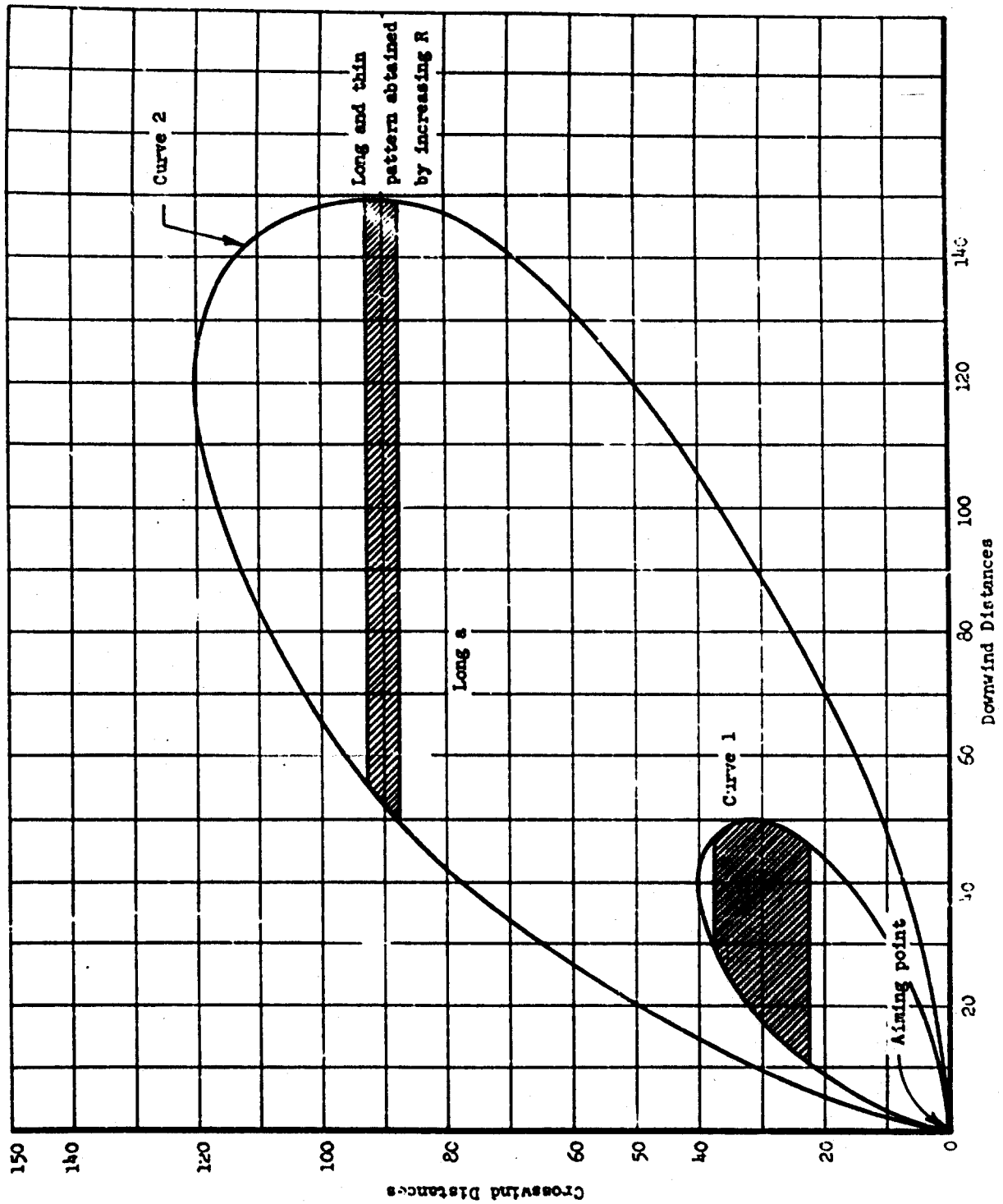


Fig. 6 VARIATION OF SHAPE OF PATTERN WITH HEIGHT OF RELEASE

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1. Design a progressive ejection system giving a mass distribution as close as possible to the theoretical distribution

$$\delta m = \frac{k}{\sigma^2} \delta m$$

2. Failing this, replace the instantaneous base ejection system by a system releasing the agent over a finite period of time.

3. Failing this, broaden the logarithmic by raising the drop mass deviation from 0.40 to 0.80.

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**VI. GROUND COVERAGE OF EXTENDED AREAS****A. Introduction**

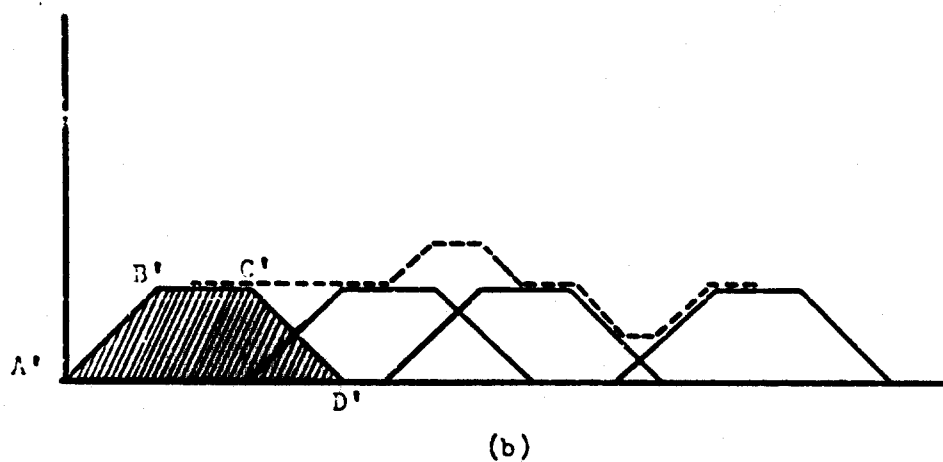
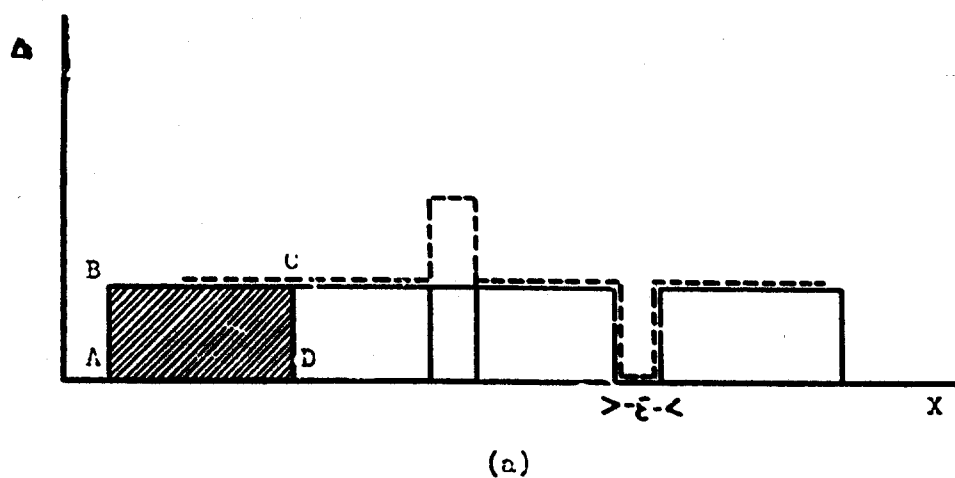
The blanketing of a large area requires that many rockets be fired. The inevitable variations of ballistic parameters cause the position of the individual contamination patterns to shift from the aiming points. Some areas on the ground may thus be within two or more contamination patterns while others receive little or no agent. The closer the aiming points, i.e., the more the individual patterns overlap, the lesser the probability that any one point on the ground will escape contamination but the greater, the expenditure in material and manpower.

Before calculating the over-all "coverage" of the target, this concept of coverage must be defined more precisely. To do so, consider the two simplified examples illustrated schematically in Fig. 7J. The first corresponds to an individual pattern of uniform density,  $\Delta$ , on the ground represented by the step function ABCD. Assume, for the sake of simplicity, that the distance between aiming points is equal to the length AD of the pattern in the direction considered on the Fig. 7. Due to the dispersion of the rockets, some patterns will overlap, causing areas to receive a dosage  $2\Delta$ , while some other areas totally escape contamination. The extent of these "uncovered" areas depends on the dispersion of the patterns.

Consider now the case of an individual pattern such that the density increases progressively from the edges of the pattern to the center. This is represented in Fig. 7 by A'B'C'D'. A small displacement of one pattern relative to its neighbor now results in the appearance of relatively large areas receiving a contamination less than  $\Delta$  but greater than zero.

Comparison of the examples shows that the identical dispersion of the two patterns results, in the first case, in small areas of zero contamination; in the second case, in larger areas covered by less than the desired densities.

Should we then conclude that the coverage in the first case is "better" than that in the second case? From a practical standpoint, should we prefer, after a CW attack, to be faced by a small number of men with unimpeded fighting potential (neglecting psychological effects) or by a larger number of men incapacitated to a greater or lesser degree? This question cannot, of



**Fig. 7** EFFECT OF TYPE OF GROUND CONTAMINATION PATTERNS  
ON COVERAGE

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course, be answered without considering the quantitative variations of incapacitation as function of dosage. The concept of coverage based exclusively on the measure of an area subjected to a predetermined degree of contamination alone appears to be deficient.

Since a comprehensive definition is unavailable, we shall have to consider the fractional coverage as the ratio:

$$\frac{\text{area receiving a contamination equal or greater than } \Delta}{\text{total target area}}$$

This, in turn, introduces a new difficulty, due to our ignorance of the distribution of the agent within the individual pattern of contamination. The ground distribution is determined by the mass distribution of the drops ejected from the rocket. In other words, rockets of equal size and identical dispersion, aimed at the same points will give different coverages depending upon the characteristics of the ejection system. Each ejection system leads to a different mathematical expression of the coverage and to a different way of computing it. Thus, no general expression of the coverage, as defined above, can be given as a function of the mass distribution  $F(d)\delta d$ .

Therefore, it will be assumed in the following that the individual patterns of contamination on the ground are step functions such as represented in (a) of Fig. 7. This particular case corresponds exactly to the ideal ejection system having the drop distribution

$$\delta m = \frac{k}{d^2} \delta d$$

and giving a step function on the ground. In other cases, such as that of the British logarithmic system, the density gradient

$$\frac{\delta \Delta}{\delta x}$$

along the edges of the pattern is not infinite and the actual coverage may be expected to be slightly higher than the values corresponding to the ideal system.

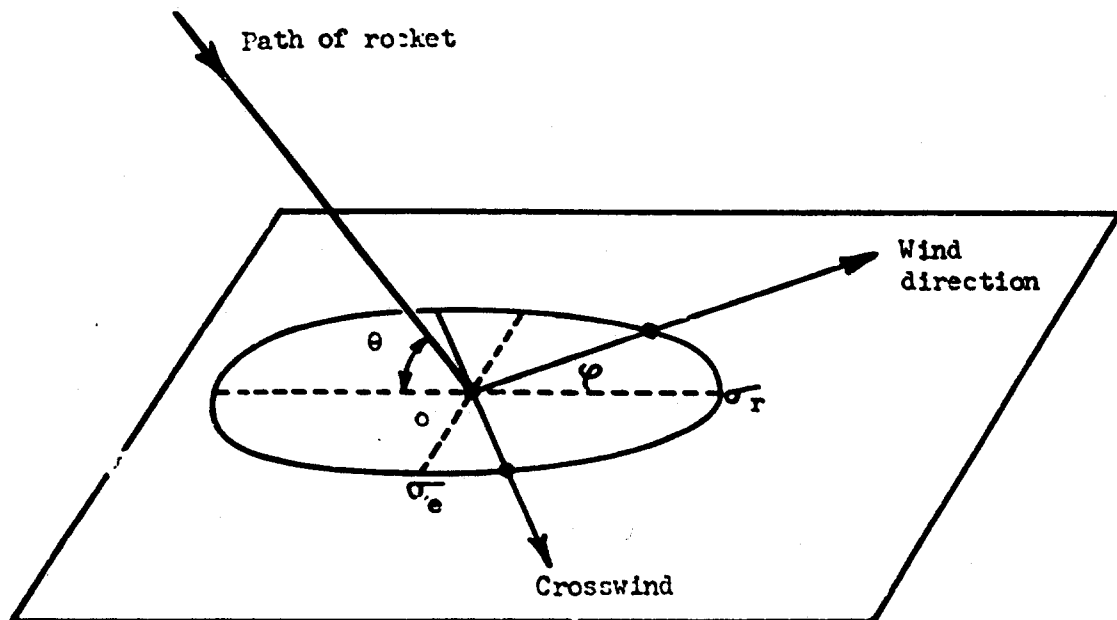
## B. Area Coverage

### 1. Cross and Downwind Dispersion

Let  $\sigma_r$  and  $\sigma_e$  be the range and lateral dispersions of a rocket aimed at a point O (Fig. 8). Let  $\varphi$  be the angle between the plane of flight

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**Fig. 8** VALUES OF CROSS AND DOWNWIND DISPERSIONS

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of the rocket and the wind direction. The crosswind dispersion is

$$\sigma_1^2 = \sigma_e^2 \cos^2 \varphi + \sigma_r^2 \sin^2 \varphi \quad (24)$$

and the downwind dispersion,  $\sigma_2$

$$\sigma_2^2 = \sigma_e^2 \sin^2 \varphi + \sigma_r^2 \cos^2 \varphi. \quad (25)$$

The dispersions of the pattern are also affected by the height at which the ejection of the agent begins. The mechanism (proximity fuze, for instance) controlling the ejection has itself a dispersion,  $\sigma_f$ . Referring to Fig. 1, we see that a variation  $\sigma_f$  along AB appears as a crosswind deviation of

$$\sigma_f \cos \theta \sin \varphi \quad (26)$$

and a downwind dispersion of

$$\sigma_f \cos \theta \cos \varphi \quad (27)$$

The dispersion due to the fuze and to errors in flight are independent. Therefore:

$$\begin{aligned} \sigma_1^2 &= \sigma_e^2 \cos^2 \varphi + \sigma_r^2 \sin^2 \varphi + \sigma_f^2 \cos^2 \theta \sin^2 \varphi \\ \sigma_2^2 &= \sigma_e^2 \sin^2 \varphi + \sigma_r^2 \cos^2 \varphi + \sigma_f^2 \cos^2 \theta \sin^2 \varphi \end{aligned} \quad (28)$$

Both  $\sigma_e$  and  $\sigma_r$  are functions of the range;  $\sigma_f$  is a function of the altitude of release.

## 2. The Coverage Function

Consider the individual area of contamination produced by one of the rockets. This area is centered at a point M and extends a distance  $\pm L_1/2$  in a crosswind direction;  $\pm L_2/2$  in a downwind direction. The deviations of M around a mean point is given by the cross and downwind dispersions in Eq. 28. Let

$d_1$  and  $d_2$  = distances between aiming points in the cross and downwind directions

$x$  and  $y$  = deviations of M from the mean in the cross and downwind directions.

Let further consider a point P of coordinate  $\xi$  and  $\eta$  on the target (Fig. 9).



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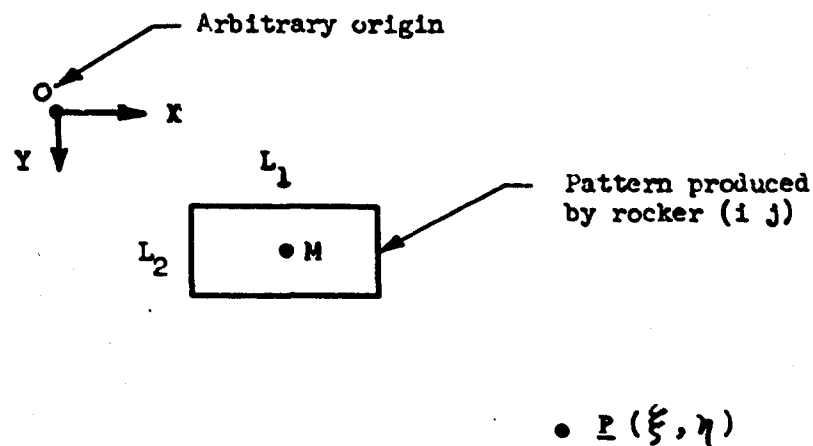


Fig. 9 PROBABILITY OF COVERAGE

The probability that point  $\underline{P}$  is covered by the contamination pattern of rocket (i, j) centered at point M ( $id_1, jd_2$ ) is:

$$P_{ij}(\xi, \eta) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-r^2}} \int_{\eta+id_1-\frac{L_1}{2}}^{\eta+id_1+\frac{L_1}{2}} \int_{\xi+jd_2-\frac{L_2}{2}}^{\xi+jd_2+\frac{L_2}{2}} \exp \left[ -\frac{1}{2(1-r^2)} \left( \frac{x^2}{\sigma_1^2} + \frac{y^2}{\sigma_2^2} - \frac{2rxy}{\sigma_1\sigma_2} \right) \right] dx dy \quad (29)$$

where

$$r = \frac{\text{cov.}(x, y)}{\sigma_1\sigma_2} \quad (30)$$

The probability that  $\underline{P}$  is not covered is

$$Q_{ij}(\xi, \eta) = 1 - P_{ij}(\xi, \eta) \quad (31)$$

The probability that  $\underline{P}$  is not covered by the pattern of any rocket is

$$Q(\xi, \eta) = \prod_{i=-\infty}^{+\infty} \prod_{j=-\infty}^{+\infty} Q_{ij}(\xi, \eta) \quad (32)$$

assuming for the moment that the target is infinite, that is, that the  $i$  and  $j$ 's assume all integral values.

The target coverage,  $\Gamma$ , is then

$$\Gamma = 1 - \frac{1}{A} \iint_A Q(\xi, \eta) d\xi d\eta \quad (33)$$

### 3. Interpretation of the Coverage Function

Equation 33 is not readily amenable to computation because it contains too many independent variables, namely the two distances  $d_1$  and  $d_2$  between aiming points, the dispersions  $\sigma_{cw}$  and  $\sigma_{dw}$ , the cross and downwind dimensions  $L_1$  and  $L_2$  of the individual area of contamination, the angle of between line of fire and wind direction and, in the case of finite targets, the size and shape of the latter.

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We must remember, however, that this expression represents a mathematical model of a system about which little is known. If and when a practical progressive ejection system is realized, its performance will undoubtedly be found to differ somewhat from the model, due to the effect of parameters difficult or impossible to estimate correctly.

In such a situation, it is idle to devote too much effort in attempting a rigorous analysis of the mathematical model. It is preferable to simplify the model so that it yields the greatest amount of practical information. Such a simplified model is valuable in outlining the general characteristics of the system and providing a starting point for research and development. As experimental data becomes available, the basic model may be refined to approach the actual system.

Returning to Eqs. 33 and 29, we notice that the presence of the correlation coefficient in the probability integrals makes it extremely difficult to compute and present the values of  $\Gamma$ . However, we observe, from Eq. 28, that this coefficient vanishes when  $\varphi = 0$  or  $\varphi = \pi/2$ , that is, when the line of fire is parallel or perpendicular to the wind direction. The correlation coefficient reaches a maximum for  $\varphi = \pi/4$  but its value is still small ( $< 0.09$ ) relative to 1 for typical values of  $\sigma_x$ ,  $\sigma_y$  and  $\sigma_z$  obtained from ballistic tables. It is not possible to indicate, at this point, the magnitude of the errors on  $\Gamma$  made by neglecting  $r$  for  $\varphi = \pi/4$ , but it is believed that these errors are small. Therefore, we shall assume that the coverage may be represented by

$$\Gamma = 1 - \frac{1}{A} \iint_A \prod_i \prod_j \left[ 1 - \frac{1}{2\pi\sigma_1\sigma_2} \iint_{ij} \exp - \frac{x^2}{2\sigma_1^2} - \frac{y^2}{2\sigma_2^2} dx dy \right] d\xi d\eta \quad (34)$$

This simplified expression, from Eq. 33 by making  $r = 0$  is exact for  $\varphi = 0$  or  $\varphi = \pi/2$  and may be slightly in error for intermediate values of  $\varphi$ .

#### 4. Pattern Shape and Disposition of Aiming Points

The two integrals within the brackets in Eq. 34 depend on the shape ( $L_1, L_2$ ) of the pattern and on the disposition of the aiming points ( $d_1, d_2$ ). We indicated earlier that the shape of the pattern (the length/width ratio) could be modified at will by adjusting the rate and height of ejection (see Fig. 6). The disposition of the aiming points, i.e., the value of  $d_1/d_2$

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for a given firing density is, of course, arbitrary. We may well ask, at this point, whether there exists a combination of  $L_1/L_2$  and  $d_1/d_2$  which would maximize the coverage.

This question can be simply answered in the particular case where  $\sigma_1 = \sigma_2$ .

Let us digress for a moment to examine the value of these dispersions. The range and ballistic dispersions of the 4, 4-1/2-inch and Honest John rockets have been plotted as a function of the relative range in Fig. 10. The points are well lined up, indicating that the dispersions are independent of the size of the rocket. At 90 per cent of the range, the  $\sigma_r = \sigma_e$ . At this relative range, therefore the cross and downwind dispersions of the pattern also are equal, as indicated by Eq. 28.

Returning to the coverage function Eq. 34, we observe that either integral within the bracket vanishes when  $L_1$  or  $L_2 = 0$ . By reasons of symmetry and from considerations of marginal increases of these integrals, it can be shown that the product of the two integrals is maximum when

$$\frac{L_1}{L_2} = \frac{\sigma_1}{\sigma_2}$$

If  $\sigma_1 = \sigma_2$ , then  $L_1 = L_2$  and, by a similar reasoning, we find that  $d_1$  must equal  $d_2$  in order to maximize the product. This, in turn, maximizes the coverage function  $\Gamma$ .

Thus, when the rockets are fired at 90 per cent of their maximum range, the patterns should be square and the aiming points, equidistant in order to obtain the maximum coverage.

Now, in covering a large area, the firing range will generally vary. Thus, theoretically at least, the shape of the patterns and the grid pattern of aiming points should vary from point to point on the target in order to obtain a constant, optimum value of the coverage throughout the target. Thus, again, practically every rocket should have a different fuze setting and different adjustment of the ejection rate. The aiming points would have to be disposed on a complicated system of intersecting lines determined by the range.

It appears preferable to design a universal system having its optimum performance at a predetermined range. The gains in time and convenience

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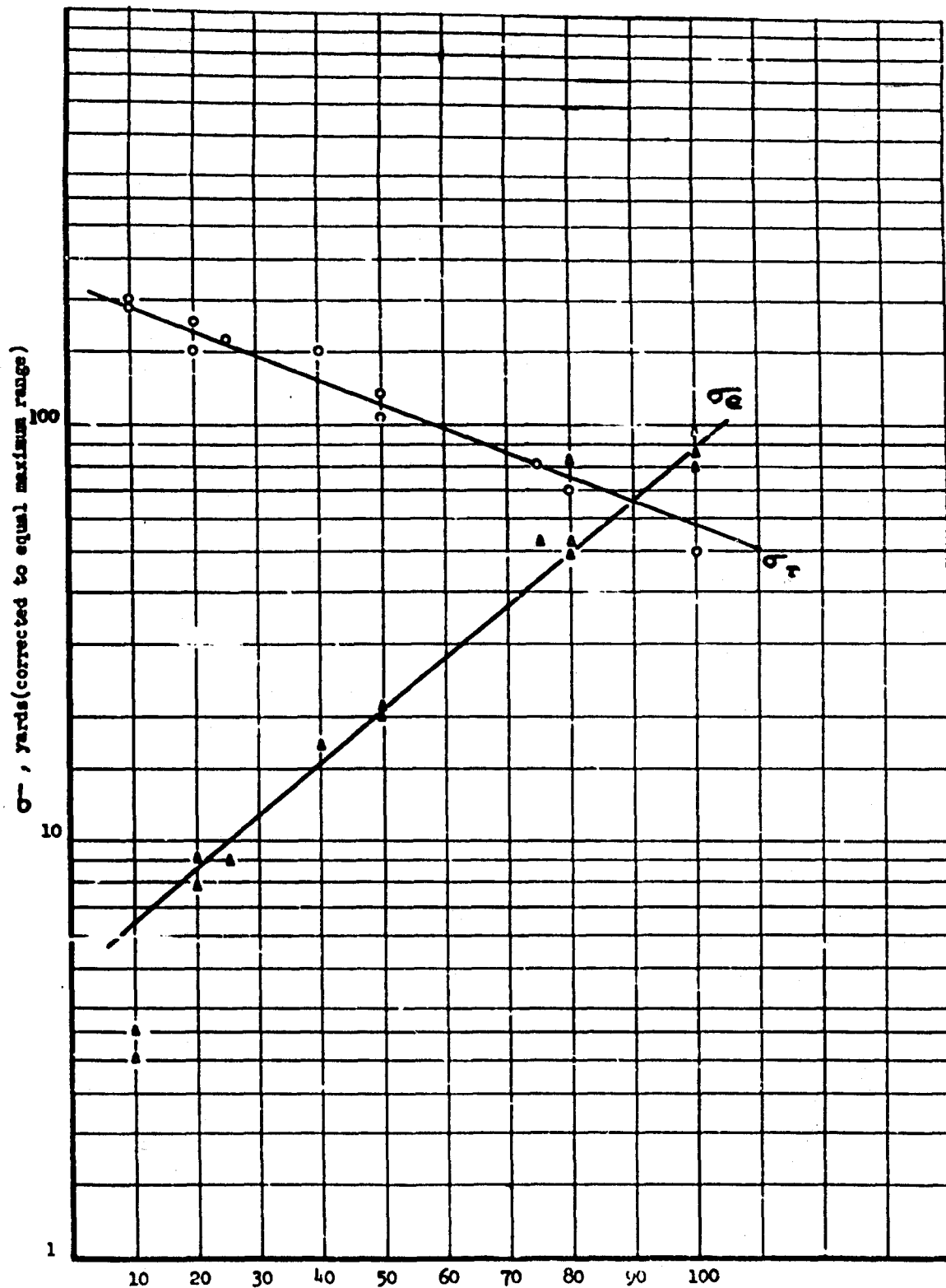


Fig. 10 BALLISTIC DISPERSION OF FIN-STABILIZED FREE ROCKETS

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under combat conditions should more than compensate for the slight decrease in efficiency.

Selection of the range for which  $\sigma_1 = \sigma_2$  offers obvious advantages in further discussing the coverage function. This range (90 per cent of maximum range) was selected although it may not be truly representative of the range encountered in tactical situations. We shall show later that the coverage is not seriously affected for other ranges and that our selection is valid.

#### 5. Values of the Coverage

The coverage function (Eq. 24) was computed for the particular case described above, i.e., when

$$\begin{aligned}\sigma_1 &= \sigma_2 \\ d_1 &= d_2 \\ L_1 &= L_2\end{aligned}$$

The values of  $\Gamma$ , the expected coverage appear in Fig. 11 as a function of  $d/\sigma$  and  $L/\sigma$ .

Thus, for instance, if the distance between aiming points is 34 yards and if each rocket gives a square contamination whose side equals 34 yards, then

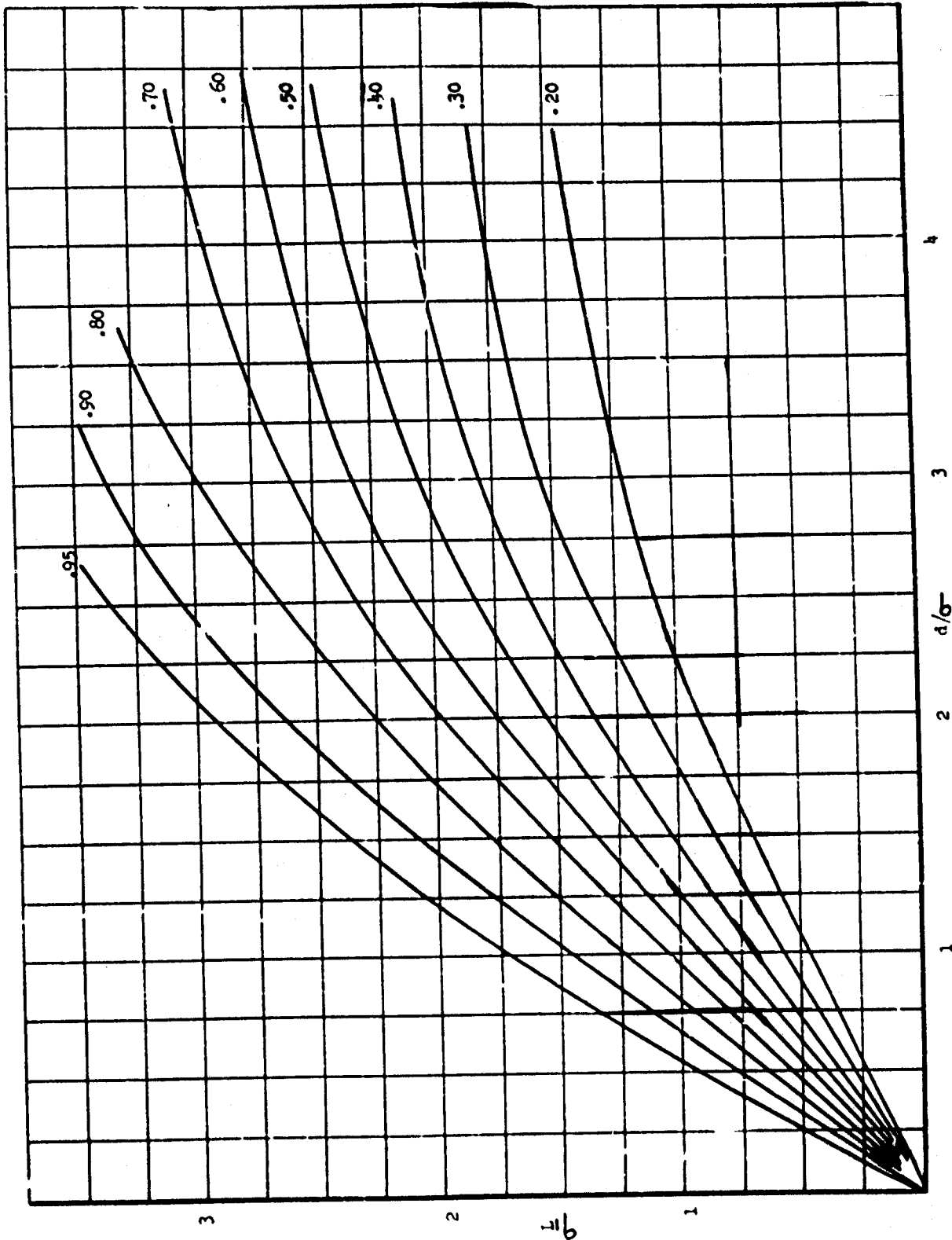
$$\frac{d}{\sigma} = \frac{L}{\sigma} = \frac{34}{68} = 0.5$$

in the particular case where the two pattern deviations are equal to 68 yards (90 per cent of range). The coverage is found to be 63 per cent. Again, suppose that 90 per cent coverage is desired. With the above-mentioned rocket, the distance between aiming points must be about 23 yards.

#### C. Discussion

If the ratio  $L/d$  is kept constant, that is, if the firing density remains the same, the coverage increases with  $L$ . This appears clearly in Fig. 12, derived from Fig. 11, by plotting  $L/d$  as a function of  $L/\sigma$  and  $\Gamma$ . In other words, the coverage is improved by increasing the size of the contamination pattern, that is, the amount of agent carried in the rocket. Expressed differently, better coverage is obtained by firing a few large rockets than by many small ones, the quantity of agent remaining the same. It is assumed,

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**Fig. 11 VALUES OF COVERAGE**

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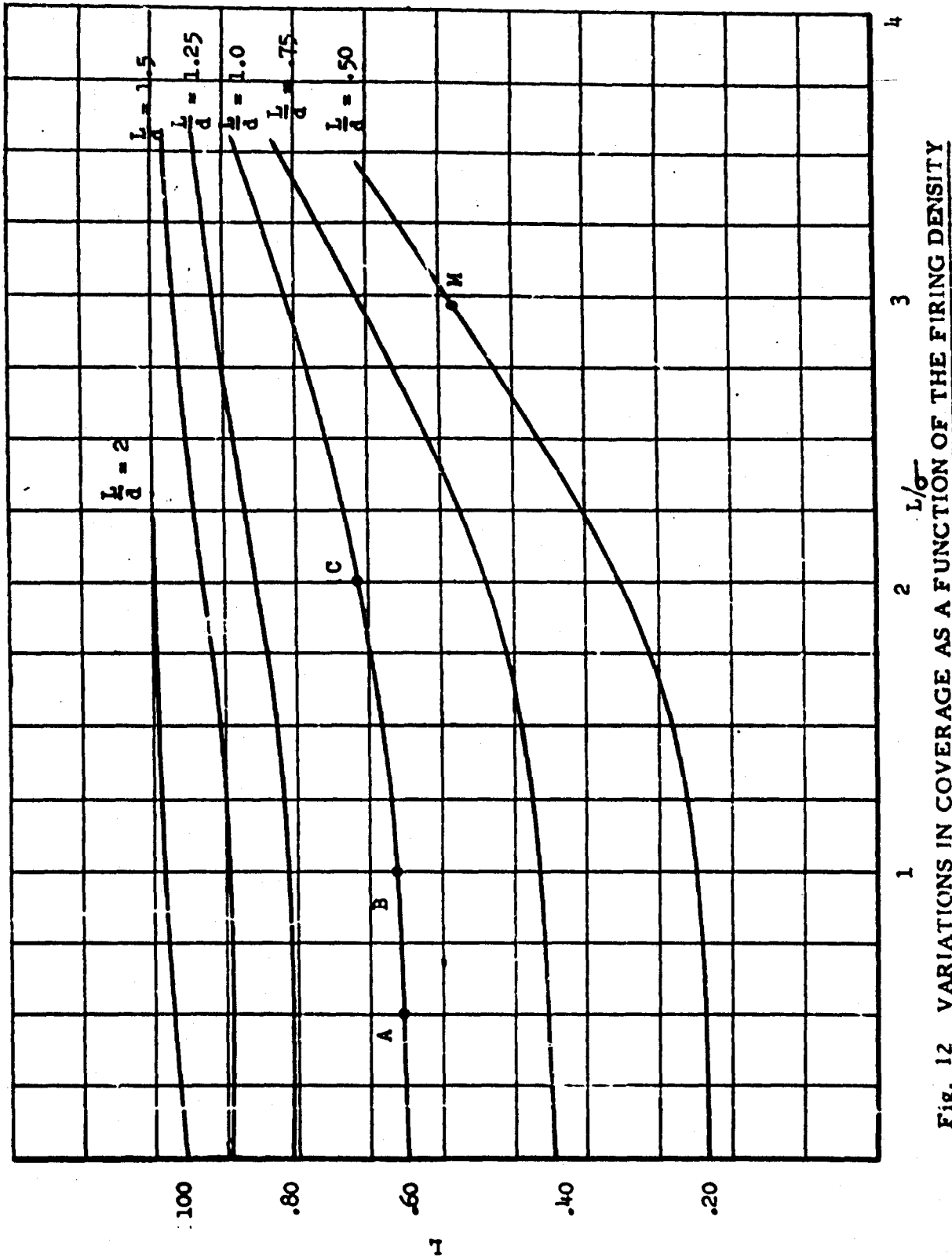


Fig. 12 VARIATIONS IN COVERAGE AS A FUNCTION OF THE FIRING DENSITY

AND ROCKET SIZE

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of course, that the ballistic and fuze dispersions are not affected by the size of the rocket.

For instance, if  $L$  is increased by a factor of 2 (points A and B on Fig. 12), that is, if the payload of the rocket is increased by a factor of 4, the coverage increases from 65 to 66 per cent. Increasing the payload by a factor of 16 (point c) raises the coverage to 71 per cent.

Inspection of the Fig. 12 shows that the gain in coverage is significant only in the region about point M where the slope of the  $L/d$  curves is greatest. This corresponds to cases where a)  $L/\sigma$  is large and b)  $L/d$  is small. We shall see later that, for practical sizes of rockets,  $L/\sigma$  is large (say  $L/\sigma > 2$ ) only when the desired contamination density on the ground is relatively small (say  $\Delta_0 = 0.1$  to  $0.3 \text{ g/m}^2$ ). Substantial improvements in coverage can be achieved only when (a) relatively low levels of contamination and (b) relatively low values of coverage (say around 50 per cent) are considered to be adequate. The coverage can be appreciably increased only by drastically increasing the size of the rocket. Therefore, except in the case mentioned above, the size of the rocket is not critical and will have to be determined on the basis of logistic considerations.

By the same token, if  $L/d$  remains constant, the coverage is increased when  $\sigma$  is decreased. In other words, if the ballistic or fuze dispersions<sup>1</sup> are improved, the area coverage,  $\Gamma$ , will increase. This conclusion is intuitively evident; better placement of the contamination patterns within the target area should reduce the overlapping of patterns and increase the coverage.

Again we notice that the effects of  $\sigma$  on the coverage are very slight when (a) the pattern of each rocket is small and/or (b) the over-all coverage is high. Therefore, in this case, the coverage will not be significantly decreased if  $\sigma$  is indefinitely increased, that is, if the rockets are fired at random throughout the target area. Thus we conclude that the time and efforts required to plot the aiming points, compute the elevation and traverse of the launcher and so on, may be eliminated at the expense of only a very slight decrease in over-all coverage on target.

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<sup>1</sup>Equations 28 show that the pattern dispersion decreases with  $\sigma_r$ ,  $\sigma_e$  or  $\sigma_f$ .

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The coverage function thus shows that the target coverage is determined mainly by the firing density, that is, by the amount of agent directed at the target. The coverage is not significantly affected by the size dispersions of the rockets when the firing density is kept constant.

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ARF Project D113  
Task X Report

## VII. DESIGN PARAMETERS

### A. Introduction

In Section V and VI we developed a number of basic relationships between the parameters of the system. It appears desirable, at this point, to leave pure speculation and examine a concrete example.

Since the number of independent variables involved in the complex system is high, the numerical example can be kept to manageable proportions only by assigning arbitrary values to some of these variables. While the example may not be truly universal, it will give an insight to the practical possibilities.

Two groups of rockets are considered in our example -- the first includes low drag rockets with relatively high terminal velocities and low impact angles. The ballistics characteristics of these rockets were computed using available flight and wind tunnel data. We assumed that the agent was ejected progressively from the rocket during the last few instants of flight, through an ejection system giving either a logarithmic distribution of drop size similar to that of the British 25 pounder or a distribution obeying the ideal inverse square law. In the second case, we assumed further that the limiting sizes of droplets were 75 and 150 microns.

We further assumed that the wind speed was 3.6 km/hr, that the wind direction made an angle of 45 degrees with the firing direction, and that the desired ground contamination density was one g/m<sup>2</sup>. We shall indicate how this specific example can be extended to other values of these parameters by very simple transformations of the tables. While this method may be considered somewhat unorthodox, it offers the advantage to present at a glance, in a simple manner, a great deal of numerical data and relationships which would be very cumbersome to present formally.

The results appear in Tables 4 to 6. The first five lines give the diameter, weight, terminal velocity, angle of impact of, and the mass of agent carried by the rocket. The mass,  $Q$ , was estimated from the payload of the rocket, taking into consideration the possible weight and volume of the ejection system. Five rocket sizes are considered in each table. Sizes smaller than 4 inches were not considered because the payload becomes

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exceedingly small, while sizes larger than 8 inches were similarly neglected because such rockets require heavy launcher and handling equipment.

Line 6 in the tables lists three possible altitudes,  $H_0$ , for initiating the release of the agent. The selection of this altitude,  $H_0$ , is limited. If it is too low, the agent may not be completely ejected when the rocket hits the ground. We recall that the rate of ejection is determined by the altitude of release. If  $H_0$  is too high, the ejection rate increases rapidly to unmanageable values. By trial and errors, a value of  $H_0$  corresponding approximately to the lowest practical value was computed and appears in the first column of each rocket size. This value was selected in such a way that the ejection ceased when the altitude was about 50 m, that is, about twice the fuze deviation.

Line 7 gives the downwind length,  $L_0$ , of the contaminated pattern at dosage and altitude,  $H_0$ . As expected the  $L_0$ 's obtained with the logarithmic ejection mechanism are shorter than those corresponding to the perfect system.

Line 8 gives the initial rate of ejection  $R_0$  in kg/sec. The rate is controlled when  $\Delta_0$  and  $H_0$  are fixed and is given by Eqs. 18 and 22.

Line 9 gives the time of fall  $t_f$  of the rocket from altitude,  $H_0$ , to the altitude zero.

Line 10 gives the time,  $t_e$ , during which the ejection takes place. We mentioned earlier that the rate of ejection had to be proportional to the altitude of the rocket in order to obtain the most efficient distribution of the agent on the ground. As the rocket falls to the ground, its altitude at time,  $t$ , is

$$H_c = H_0 - vt \sin \theta$$

and the rate of ejection must be

$$R_t = R_0 \frac{(1 - \frac{vt}{H_0} \sin \theta)}{H_0}$$

During  $\delta t$ , the quantity of agent ejected is

$$\delta q = R_t \delta t$$

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At the end of ejection, the integral of  $\delta q$  must equal the quantity,  $Q$ , of agent initially present in the rocket:

$$Q = \int_0^{t_e} R_t \delta t$$

after suitable manipulation, the time of ejection is found to given by

$$t_e = \frac{H_o}{v \sin \theta} \left( 1 - \sqrt{1 - \frac{2Q}{R_o} \frac{v \sin \theta}{H_o}} \right)$$

The width of the pattern in the crosswind direction is given in line 11. This is the projection of the velocity vector in the crosswind direction multiplied by the time of ejection:

$$w = v \cos \theta \sin \theta t_e$$

Line 12 gives the final altitude,  $H_f$ , at which ejection ceases:

$$H_f = H_o - v t_e \sin \theta$$

As the altitude decreases, the length (downwind) of the pattern decreases. The pattern on the ground is therefore trapezoidal with the two parallel sides in the wind direction. Line 13 gives the mean downwind length of the pattern. The mean length,  $L_m$ , is

$$L_m = \frac{L_o}{2} \left( 1 - \frac{H_f}{H_o} \right)$$

Line 14 gives the ratio  $L_m/w$ . This is a figure of merit of the regularity of the pattern. A figure greater than 1 indicates that the contaminated area has its greatest length in the wind direction.

The last line gives the area of the contaminated pattern:

$$a = w L_m$$

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The area of the patterns obtained with ideal ejection system is, as expected, equal to

$$a = \frac{Q}{\Delta_0}$$

Since the agent is distributed uniformly on the ground, the areas obtained with the logarithmic system differ from the preceding by a factor of 0.275. This is the value of term

$$\frac{1 - e^{-2\sigma^2}}{\sqrt{2\pi} \sigma}$$

as indicated in Eq. 20.

**B. Interpretation**

Inspection of the tables indicate that the parameters relative to the release of the agent (rate and time of ejection) are not modified whether the logarithmic or ideal system is used. Only the lengths of the pattern in the downwind direction are altered. The less uniform the distribution on the ground, (the greatest the departure of the mass distribution of the steps from the universe square law), the smaller the length of the pattern in the downwind direction. Consequently, Tables 4 and 5 differ only by lines 7, 13, 14, and 15. For this reason, the table corresponding the low drag rocket with a logarithmic ejection system has not been included here. It can be easily derived from Table 6. Minute differences between Tables 4 and 5 stem from the fact that this similarity was recognized only after computation of these tables.

All results in Tables 4 to 6 were obtained by assuming that the density of contamination is  $\Delta_0 = 1 \text{ g/m}^2$ . These tables are still valid for any other density,  $\Delta_1$ , provided that some simple modifications are introduced. These modifications appear immediately by inspection of the formulas given in Section V. They consist in multiplying lines 6, 7, 9, 10, 11, 12, and 13 by  $\sqrt{\Delta_0 / \Delta_1}$ ; by dividing line 8 by  $\sqrt{\Delta_0 / \Delta_1}$ ; by multiplying line 15 by  $\Delta_0 / \Delta_1$ ; and by leaving line 14 unchanged.

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Table 4  
EJECTION PARAMETERS

	4-1/2	5	6	7	8
1. Rocket Diameter, in.	85	112	172	247	345
2. Rocket Weight, lb	2.15 10 <sup>4</sup>	2.4 10 <sup>4</sup>	2.7 10 <sup>4</sup>	2.9 10 <sup>4</sup>	3.0 10 <sup>4</sup>
3. v Terminal, cm/sec	67	63	60	57	50
4. Impact Angle, deg.	3	5	10	20	47
5. Weight of Agent, kg	125 150 200	125 150 200	175 202 250	200 250 300	275 340 350
6. Ejection Altitude, H <sub>e</sub> , m	225 270 340	225 270 340	315 360 450	360 450 540	500 540 630
7. Initial Length of Pattern, L <sub>0</sub> , m	14 17 22	17 21 28	30 35 44	41 53 63	70 76 88
8. Initial Rate of Ejection, R <sub>e</sub> , kg/sec	0.63 0.75 1.0	0.59 0.70 0.95	0.74 0.85 1.06	0.84 1.06 1.25	1.42 1.56 1.82
9. Time of Fall, t <sub>f</sub> , sec	0.31 0.22 0.19	0.45 0.27 0.19	0.50 0.33 0.25	0.53 0.45 0.35	1.08 0.84 0.65
10. Time of Ejection, t <sub>e</sub> , sec	17 13 9	35 20 14	46 31 24	69 49 39	170 129 95
11. Width of Pattern, w, m	71 112 172	30 92 161	58 132 196	78 150 212	28 168 200
12. Final Altitude, H <sub>f</sub> , m	178 240 340	143 225 330	215 310 410	285 420 500	275 370 500
13. Mean Length of Pattern, L <sub>m</sub> , m	11 20 33	4 11 22	5 10 17	4 9 13	1.6 3 56
14. L <sub>m</sub> /w	3000	5000	10,000	20,000	47,000
15. A <sub>0</sub> -A <sub>1</sub> , m <sup>2</sup>					

$w_0 = 10^2$  cm/sec

$\gamma = 45^\circ$

$A_0 = 1$  g/m<sup>2</sup>

Inverse square law: ejection between 75 and 150 ft

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Table 5  
EJECTION PARAMETERS

1. Rocket Diameter, in.	4-1/2	5	6	7	8
2. Rocket Weight, lb	85	112	172	247	345
3. $v$ Terminal, cm/sec	$2.15 \cdot 10^5$	$2.4 \cdot 10^4$	$2.7 \cdot 10^4$	$2.9 \cdot 10^4$	$3.0 \cdot 10^4$
4. Impact Angle, deg	67	63	60	57	50
5. Weight of Agent, kg	3	5	10	20	47
6. Ejection Altitude, $H_0$ , m	110 125 150	125 150 200	170 200 250	225 250 300	275 300 350
7. Initial Length of Pattern, $L_0$ , in	55 62 75	62 74 99	84 100 124	112 125 150	138 148 172
8. Initial Rate of Ejection, $R_0$ , kg/sec	12 14 17	18 22 29	31 35 44	49 53 63	70 76 88
9. Time of Fall, $t_f$ , sec	0.55 0.63 0.75	0.53 0.71 0.95	0.70 0.85 1.06	0.95 1.05 1.46	1.42 1.56 1.82
10. Time of Ejection, $t_e$ , sec	0.39 0.31 0.24	0.45 0.28 0.19	0.49 0.33 0.26	0.60 0.45 0.35	1.08 0.84 0.65
11. Width of Pattern, $w$ , m	23 18 13	35 20 14	46 33 24	69 48 39	170 129 95
12. Final Altitude, $H_f$ , m	32 70 112	30 92 159	35 132 177	33 146 210	38 108 200
13. Mean Length of Pattern, $L_m$ , m	35 40 61	35 65 90	55 79 110	76 97 127	71 95 126
14. $L_m/w$	1.5 2.1 4.5	1.3 3.1 7.0	1.2 2.4 4.6	1.1 1.8 3.0	0.5 0.8 1.4
15. Area, $a$ , $m^2$	500	1240	2,600	5,100	12,000

$H_0 = 10^2$  cm/sec ( $1.5$  km/hr)

$\gamma = 45^\circ$

$A_0 = 187/m^2$

Logarithmic ejection,  $d_0 = 140 \mu$ ,  $\sigma = 0.46$



Table 6  
EJECTION PARAMETERS

	4	4-1/2	5	7	8
1. Rocket Diameter, in.	64	85	112	247	345
2. Rocket Weight, lb	6,000	6,000	6,000	6,000	6,000
3. $v$ Terminal cm/sec	35	35	35	35	35
4. Impact Angle, $\theta$	1.5	3	5	20	41.5
5. Q Agent, kg	45	75	100	150	265
6. Ejection Altitude, m	31	135	180	135	180
7. Initial Length, $L_0$ , m	28	47	63	47	63
8. Initial Rate of Ejection, $R_0$ , kg/sec	0.13	0.22	0.29	0.22	0.29
9. Time of Fall, $t_f$ , sec	0.075	0.033	0.026	0.022	0.018
10. Time of Ejection, $t_e$ , sec	26	12	99	42	28
11. Width of Pattern, $w$ , m	20	64	81	19	48
12. Final Altitude, $H_f$ , m	60	125	162	71	110
13. Mean Length, $L_m$ , m	2.3	10	18	2.5	2.2
14. $L_m/w$	1,500	3,000	5,000	20,000	41,500
15. Area, $a$ , m <sup>2</sup>					

$W = 10^2$  cm/sec (3.6 km/hr)

$\theta = 45^\circ$

$\Delta = 1$  gr/m<sup>2</sup>

Inverse square law: ejection between 75 and 150 ft.

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Thus, to obtain the ejection parameters corresponding to a ground density of  $\Delta_1 = 0.1 \text{ g/m}^2$ , the height of ejection must be multiplied by 3.15; the rate of ejection becomes smaller by a factor of 3.15, the mean length and width of the pattern are both multiplied by 3.15, and the area becomes 10 times larger than the area for  $\Delta_0 = 1 \text{ g/m}^2$ .

Comparison of Tables 4 and 6 shows that the minimum altitude of ejection is considerably decreased by using low drag rockets. This is due partly to the smaller angle of impact, partly to the higher terminal velocity of these rockets. Consequently, much more regular patterns (lower  $L_m/w$ ) are obtained by using the low drag rockets.

However, these rockets require higher ejection rates which may introduce difficulties in designing a practical ejection mechanism. These difficulties should be minimized in the case where it is desired to obtain only low values of contamination on the ground.

It was pointed out earlier in the particular case where the rockets are fired at 90 per cent of their range, that the down and crosswind dimensions of the contamination pattern had to be similar. Therefore, in order to optimize the coverage over a large target, low drag rockets should preferably be used.

It is realized that, in covering very large targets, the range may vary considerably. Theoretically the shape of the individual patterns should be varied so as to match the pattern with the local down and crosswind dispersions. This would require that the altitude of release,  $H_0$ , and the rate of release,  $R_0$ , be adjusted for each range. This solution does not appear to be practical under combat conditions. It appears preferable to design the ejection system around the set of conditions corresponding to the mean range likely to be encountered in a tactical situation. We do not believe that the decrease in coverage resulting from the mismatching between patterns and deviations at extreme ranges would be significant.

We indicated in Section VI that the overall coverage was somewhat improved by decreasing the relative overlapping of the patterns. This was accomplished by increasing the dimensions of the individual pattern relative to the dispersions on the ground. In other words, the coverage was slightly improved by using fewer, larger rockets instead of many small ones, the quantity of agent remaining the same.

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We may now examine the results in Tables 4 to 6 with respect to the influence of the size of the rocket on the ejection parameters.

We first observe that the size of the rocket does not appear to affect the lowest value of  $L_m/w$ . In this respect, at least, all sizes are equally efficient. We then see that as the size increases the rate of ejection also increases. However,  $R_0$  does not increase as fast as the quantity of agent carried. In other words, the ejection system for the largest rockets is likely to be less bulky and heavy, in relation to the quantity of agent. Furthermore, the payload of larger rockets is considerably larger when compared to the total weight of the rocket. This is illustrated in Table 7, giving the number and weight of rockets to blanket an area of  $3 \times 10^6 \text{ m}^2$  at a density of one  $\text{g/m}^2$ .

Table 7  
**NUMBER AND WEIGHT OF ROCKETS REQUIRED  
TO COVER A  $3.10^6 \text{ m}^2$  AREA**

	Inverse Square		Logarithmic	
	Number	Weight, lb	Number	Weight, lb
8-inch Rockets	64	22,000	250	86,000
4-1/2-inch Rockets	1000	80,000	3800	300,000

The saving in weight, using the larger rocket, is considerable. However, no considerations were taken here of the weight of auxilliary equipment, such as launchers or rocket handling devices. Furthermore, we indicated that the given values of coverage applied only to infinite targets. When the number of rockets fired at the target falls to about 16, the coverage begins to decrease and can be maintained to its desired value only by increasing the density of the aiming points.

Thus, if the specified target ( $3 \times 10^6 \text{ m}^2$ ) is about square and a contamination of  $0.1 \text{ g/m}^2$  is desired, only twenty-five 8-inch logarithmic rockets are required, five in either direction. The 8-inch rocket appears to represent the largest size to be used under these conditions. If, however, the target is likely to have a minimum

dimension of, say 300 m, then smaller rockets should be used to conserve the versatility of the weapon in various tactical situations. The following table suggests the preferred rocket sizes determined along the preceding considerations

Table 8  
**PREFERRED SIZE OF ROCKET FOR LARGE AREA COVERAGE**

Desired Contamination Density (g/m <sup>2</sup> )	Logarithmic Ejection System (inch)	Ideal Ejection System (inch)
0.1	4-1/2	4
1.0.	7	5

The results on Table 6 to 8 were calculated for an arbitrary value of  $W_0$ , the wind velocity. We suspect that at higher wind speeds, the contamination pattern will become longer in the wind direction. It is not possible, as in the case of  $\Delta$ , to give a simple correction factor to obtain the ejection parameter corresponding to a wind speed,  $W_1$ . It is possible, however, to obtain a good approximation by multiplying lines 7, 8, and 13 by  $\sqrt{W_1/W_0}$ ; dividing lines 6, 9, 10, 11, and 12 by  $\sqrt{W_1/W_0}$ ; multiplying line 14 by  $W_1/W_0$  and leaving line 15 unchanged. Thus, the optimum height of ejection should be halved when the wind speed is

$$W_1 = 4 \times 3.6 = 14.4 \text{ km/hr.}$$

and the rate of ejection should be doubled. The pattern will become twice as long and half as wide as the original pattern.

## VIII. EJECTION SYSTEMS

### A. Pressure Ejection Through Rocket Head

The ejection system must discharge the agent at the proper rate, and produce the correct distribution of droplet sizes to give uniform density of agent on the ground. To obtain a uniform distribution of agent on the ground, the mass distribution of droplets must satisfy an inverse square law

$$\delta m = \frac{K}{d^2} \delta d$$

The ejection rate must be about 200 lbs/sec for the 8-inch rocket. This might be accomplished by a piston actuated by gases generated from a propellant composition. The propellant granulation would be one that would form increasing surface as the propellant burned, i. e., a very progressively burning shape. The rocket walls would be provided with tapered slots closed by a membrane or plugs that would blow out at the correct liquid pressure. When the piston exerts sufficient pressure on the liquid, the slots are opened and the piston will move. As the piston moves, the slots are uncovered, and propellant gases are vented to the atmosphere through the head of the rocket. Thus by proper selection of groove dimensions and propellant burning rate, the correct discharge of liquid may be maintained.

This system appears quite feasible. However, the problem is quite complex and is not readily analyzed. The idea should be tested and the design of such a device should be determined experimentally. Even when the orifice or groove sizes are proper for the correct discharge rate, these may result in the wrong particle size distribution from the moving rocket. The number of grooves or orifices and their dimensions must be adjusted to produce the desired particle sizes as well as the correct discharge rate. The design of nozzles to produce large droplets cannot be determined by analytical methods now, because we cannot define the mechanisms by which the droplets are formed. The problem should yield to a logical experimental approach.

**B. Double-Base Ejection**

We indicated earlier that, to obtain a uniform distribution of the agent on the ground, the mass distribution of the ejected droplets must satisfy an inverse square law

$$\delta m = \frac{K}{d^2} \delta d$$

Realization of such a system is probably impossible, chiefly due to the requirement for sharp cut-offs of the distribution at both low and high ends. It appears possible, however, to approximate the ideal distribution by using two or more logarithmic ejection systems. This is illustrated in Fig. 13 giving the ground density in a downwind direction produced by three different ejection systems. The plain curve corresponds to the ground density obtained with the single logarithmic distribution of the British 25 pounder. This distribution has the following characteristics:

$$d_m = 170 \mu, \sigma = 0.40$$

The step function results from a drop distribution following the inverse square law. The dashed curve was computed by assuming that the drop distribution was the aggregate of two logarithmic functions properly selected. These two functions were selected by trial and error to obtain the greatest coverage and most uniform ground density. These two distributions were found to have the following characteristics:

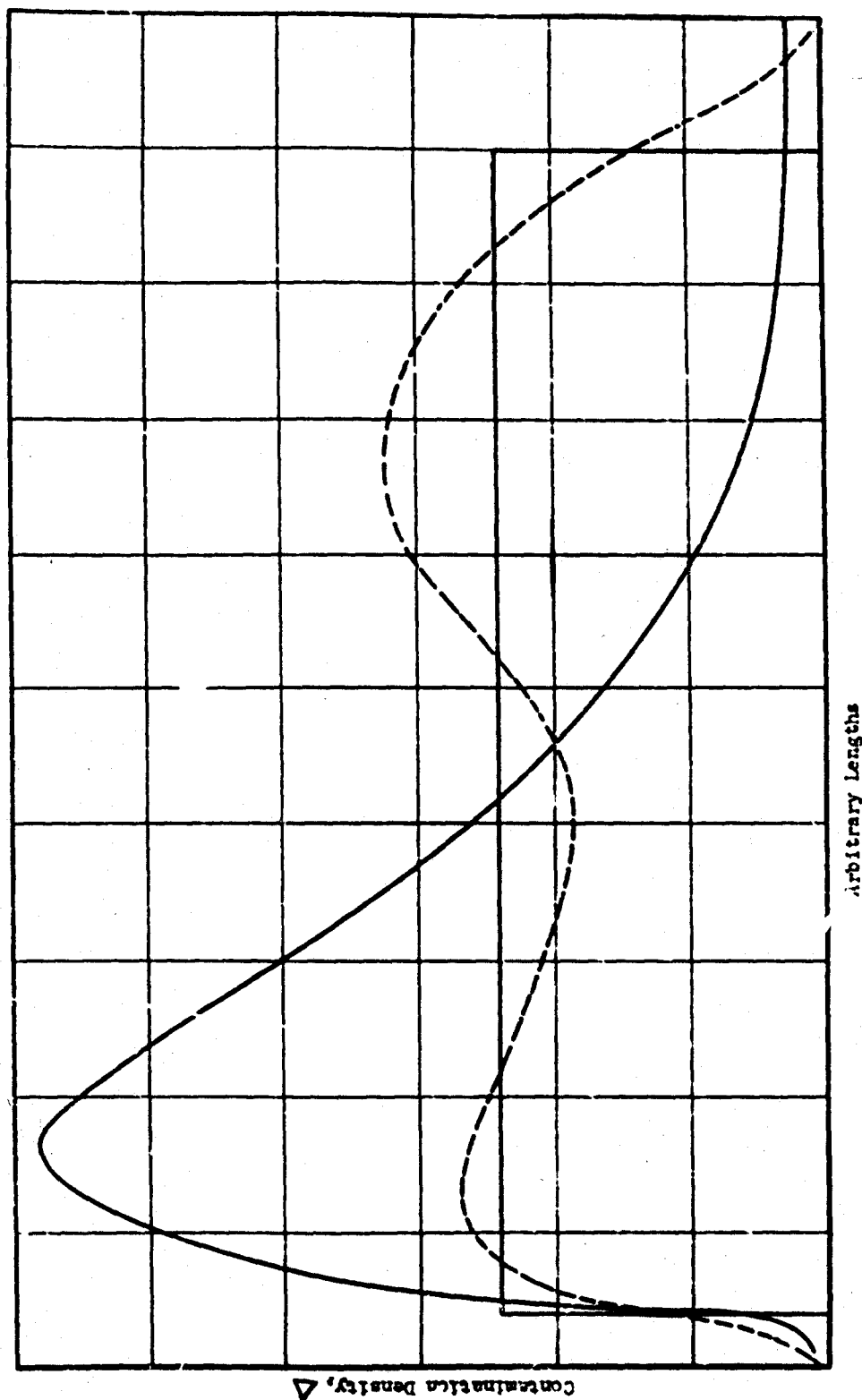
$$a) d_m = 163 \mu, \sigma = 0.547$$

$$b) d_m = 72 \mu, \sigma = 0.180$$

Each distribution was assumed to correspond to the ejection of 50 per cent of the entire amount of agent contained in the rocket.

All three systems involve the same quantity of agent, that is, the areas under each curve are identical. The duplex system gives a ground density varying about the average. At some points the density is too low, at other points, it is too high but the variations are minor and the agent is much more uniformly distributed as in the Porton curve. The right-hand cut-off, corresponding to the smallest drops, is reasonably sharp.

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**Fig. 13 DUPLEX EJECTION**

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By using three logarithmic distributions, there is little doubt that the ideal drop function could be approached even more closely.

At this stage, it is impossible to predict whether the mean diameter and the diameter variance  $\sigma$  can be arbitrarily selected. Probably, the break-up of the largest droplets in the air stream will limit the mean diameters. Fortunately, the influence of the distribution around the largest diameters is not critical. Figure 13 shows that the ground density cut-off is always sharp at this point. We believe that a reasonably efficient ejection system can be realized by combining two, or, at most, three logarithmic distributions.



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**IX. CONCLUSIONS**

The desirability of a weapon system for covering large areas with liquid sprayed from a rocket during its terminal flight is dependent upon the development of a system for ejecting the agent from the warhead. The base ejection system in current use does not produce the optimum ground contamination pattern. Ejection should take place over a finite time and produce the correct drop size distribution for uniform ground contamination. Information available at the present time does not permit an analytical approach to the design of an ejection mechanism which will produce the desired distribution of large droplets.

Large artillery rockets are more efficient vehicles for spraying large areas with liquid drops than small rockets.

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**X. RECOMMENDATIONS**

It is recommended that additional time and effort be devoted to the study of systems for ejecting liquids from shells and rockets to form large droplets. This study should include well-planned experimental investigations